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ABSTRACT

Information on thermal properties of oil sands is rather limited in the literature. The properties reported are usually based on measurements on disturbed core materials under ambient laboratory conditions. Realizing the inadequacy of such values to represent actual field conditions at *in situ* thermally stimulated production facilities, a transient state thermal test cell has been developed for thermal conductivity and thermal diffusivity testing of soil and rock cores.

A one-dimensional radial heat transfer theory was used to derive the thermal conductivity and thermal diffusivity equations that support the thermal testing apparatus. Careful considerations to justify the assumptions inherent to the theory were made during the development of the thermal test cell. Operational temperatures ranging from 20 °C to 200 °C and pore fluid pressures up to 10 MPa may be applied to the system. Together with the provision of a vertical confining load of up to 440 kN, *in situ* pressure and temperature conditions may thus be simulated during thermal testing.

Test results for dry and water-saturated quartz sand as well as remoulded and undisturbed Athabasca oil sand samples are given. Analyses of the results show that thermal properties of oil sand are significantly affected by the material itself, its density and degree of saturation, proportions and types of the saturants, as well as ambient temperature. Both the thermal conductivity and the thermal diffusivity of a partially or fully liquid saturated oil sand decrease with increasing temperature. The two properties also decrease with increasing bitumen saturation. An increase in the degree of liquid saturation of the oil sand enhances its thermal conductivity and thermal diffusivity. Higher thermal conductivity and thermal diffusivity values are also expected for oil sands of higher densities. The importance of thermal testing on undisturbed core specimens, as opposed to remoulded or reconstituted ones, to obtain more representative results is also demonstrated.

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LIST OF SYMBOLS

Since it is quite common that a single symbol may be used by engineers of different disciplines to represent different variables, it would be prudent to outline a consistent set of symbols used for the current study as shown below:

Symbol	**Meaning**
General	
A_x	Cross-sectional area (m^2)
G	Specific gravity (dimensionless)
H	Coefficient of heat transfer (W/m^2 °C)
R	Thermal resistance (m^2 °C/W)
R_o	Radius of sample (m)
S	Degree of saturation (percent)
T	Temperature (°C)
V	Constant surface temperature of sample (°C)
V_o	Initial sample temperature (°C)
V_1	Initial medium temperature (°C)
Z, L, l	Distance, length, thickness (m)
ΔL	Change in length (m)
ΔR	Maximum axial flow error (dimensionless)
ΔT	Change in temperature (°C)
c	Specific heat (J/g °C)
d	Wall thickness of probe heater (m)
d_o	Diameter of probe heater (m)
k	Thermal conductivity (W/m °C)
$k_{\perp}$	Thermal conductivity perpendicular to the optic axis of a crystal (W/m °C)
$k_{\parallel}$	Thermal conductivity parallel to the optic axis of a crystal (W/m °C)
n	Porosity (percent)
q	Rate of heat (energy) flow (W)
q_l	Power input per unit length (W/m)
q_a	Rate of heat flow per unit area (W/m^2)
r	Radial distance (m)
r_o	Radius of probe heater (m)
t	Time (s)
α	Thermal diffusivity (m^2/s)
ρ	Density (g/cm^3, kg/m^3)
ω	Moisture content (percent)

Subscripts

$_b$	Bitumen
$_o$	Oil
$_s$	Solids
$_w$	Water
$_{o,1}$	(to indicate different materials)

Functions

E_1	Exponential integral
J_0	Bessel function of order 0
J_1	Bessel function of order 1
e	Exponential function
δ_n	($_n$=1,2,3,...) Positive roots of the function, $J_0(R_0\delta)=0$
γ	Euler's constant = 0.57722
π	Pi = 3.14159

Self-defined functions

$\beta_n = R_0\delta_n$

$\tau = \alpha t/R_0^2$

$a_n = \alpha\delta_n^2$

$\psi = 2d/r_0$

$\xi = k_1/k$

$\eta = \rho_1 c_1/\rho c$

$\varnothing(t)$ = (temperature as a function of time)

$_n$ = 1,2,3,...

$A_0, A_1, A_2, \ldots, A_7$,
$W_1, W_2, W_3, \ldots, W_6$,
A,B,C,D, and b = (coefficients/constants)

λ, x, u = (variables)

CONVERSION FACTORS

For convenience in comparing values given in Imperial/U.S. customary units and *SI* units of measurement, the following conversion table is provided:

Multiply	*By*	*To obtain*
1 ft	0.3048	1 m
1 in	0.0254	1 m
1 darcy	9.869×10^{-13}	1 m^2
1 darcy	9.678×10^{-4}	1 cm/s
1 ft^2/s	0.09290	1 m^2/s
1 lb/ft^3	0.01602	1 g/cm^3
1 psi	6.8948	1 kN/m^2
1 bar	100	1 kN/m^2
1 atm	101.3250	1 kN/m^2
1 mm of Hg	0.13332	1 kN/m^2
1 cal	4.1868	1 J
1 Btu	1055	1 J
1 cal/cm s °C	418.68	1 W/m °C
1 Btu in/ft^2 hr °F	0.14423	1 W/m °C
1 Btu/ft hr °F	1.73074	1 W/m °C
1 cal/g °C	4.1868	1 J/g °C
°F	$T(°C)=5*(T(°F)-32)/9$	°C
°C	$T(K)=T(°C)+273$	K
°API	$G=141.5/(131.5+°API)$	

1. INTRODUCTION

1.1 Statement of Problem

As the world is becoming more and more energy-conscious, much research has been done in devising the optimum means to tap the vast hydrocarbon reserves buried underneath the earth crust. The recovery method for conventional light oil is relatively simple compared to the methods used for recovering heavy oil, which is highly viscous and immobile under ambient reservoir conditions. To enhance the mobility of the heavy hydrocarbon, thermal methods (such as cyclic steam stimulation, steam or water flooding, and *in situ* combustion) are generally used. Reservoir temperature and pressure conditions may be drastically altered during the thermal recovery process.

Various numerical and analytical models have been proposed by different researchers in an attempt to simulate reservoir performance. In order that these models can yield meaningful results, accurate input parameters that describe the reservoir and the boundary conditions are essential. Among the many variables that characterize the reservoir, thermal properties of the hydrocarbon deposit and its adjacent formations are some of the important parameters.

In the geomechanical analyses of stresses and deformations in heated oil sands formations, thermal properties of oil sands are also required. With particular interest in the oil sand deposits in Alberta, the author carried out a literature search and found that information on the thermal properties of oil sands is rather limited. The thermal property values, if available, are mostly based on results from testing of remoulded or reconstituted oil sand samples under room temperature and atmospheric pressure conditions.

1.2 Objectives of Thesis

The main objective of this research is to develop an apparatus and testing procedure to measure thermal conductivity and thermal diffusivity properties of oil sands at temperatures, pressures and saturations encountered in reservoirs during thermal stimulation processes. To ensure that representative results are obtained, the apparatus should be designed for testing of natural (or undisturbed) oil sand core samples. A transient state thermal test cell has been devised for this purpose.

The selection of appropriate methods of analysis of the thermal testing procedures, to allow correct interpretation of the thermal tests performed, serves as the second objective of this study. Current methods of analysis published in the literature are found to be inadequate to represent the thermal diffusivity testing procedure. The methods are subsequently extended for better representation. The development of the thermal test cell and the analytical methods for the testing procedures thus form the backbone of this thesis.

The third objective of this thesis is to check the adequacy of the proposed testing procedures and analytical methods in obtaining reasonably accurate test results by comparing measured values with other data. A selected number of samples of Athabasca oil sands are tested for this purpose.

It is believed that the thermal testing program carried out for the current study will shed some light on the importance of undisturbed sample testing under simulated field conditions. Furthermore, this research also serves to provide additional information on the thermal properties of Athabasca oil sands.

1.3 Factors Affecting Thermal Properties of Oil Sands

Table 1.1 lists the major factors that affect the three major thermal properties, namely, thermal conductivity, thermal diffusivity and specific heat of oil sands. The dominating factors are catagorized into four groups.

It should be intuitively clear that the material itself, which includes the types of mineral grains, the soil structure and its density, poses as a significant factor in controlling the thermal properties of oil sands. As long as the mineral grains and the density are the same, specific heat of the material should not be affected too much by the extent of grain to grain contacts in the soil structure.

As recognized by many investigators, the degree of fluid saturation plays a signicant role in determining the thermal properties of a material. However, there is a difference in opinion on the current methods of thermal conductivity evaluation. Some researchers (e.g. Somerton, Keese and Chu, 1974) suggest that there is no difference in thermal conductivity whether the non-wetting phase is oil or air while others (e.g. Cervenan, Vermeulen and Chute, 1981) argue that an oil/bitumen saturation parameter should be included if a proper correlation analysis is to be made. Therefore, the effects of bitumen and water proportions on thermal conductivity and diffusivity are classified as uncertain.

Since most of the research performed to determine thermal properties of oil sands is limited to homogeneous and isotropic materials, the effects of non-homogeneity and anisotropy on thermal conductivity and thermal diffusivity are uncertain. Specific heat is a parameter that depends mainly on the weighted proportions and types of the mineral grains and fluid saturants. Therefore, the effects of uniformity on specific heat should be low.

It is well documented in the literature that temperature plays a dominating role in affecting the thermal properties of a material. However, the effects of confining pressure on such properties have not been studied extensively. Some pressure dependence of thermal properties of fractured rocks is realized by many investigators. The increase in thermal conductivity with pressure is mainly attributed to the closing of fractures or discontinuities in the rock mass. Since oil sands are generally intact and have low compressibilities, it is believed that pressure effects on thermal properties should be small. However, if the sands are interspersed with compressible clay seams, the effects of confining pressure may be felt.

As long as the effective confining pressure stays constant, the effects of pore fluid pressure on thermal properties of oil sands are found to be low. Since the nature of the material should not change too drastically over a wide pressure range, its specific heat should also stay relatively constant.

1.4 Scope of Thesis

As mentioned previously, the current research concentrates on the development of a thermal test cell that can be used to measure thermal properties of oil sand samples. However, this work is limited to the measurement of thermal conductivity and thermal diffusivity as specific heat measurement methods are well documented (e.g. Smith-Magowan, Skauge and Hepler, 1982). Nevertheless, attempts will be made to estimate specific heats of oil sands from measured values of thermal conductivity, thermal diffusivity and density.

Since a study of all the factors that affect the thermal properties of oil sands (Table 1.1) requires a lengthy testing program, it is proposed to limit the scope of the research to the consideration of a few of the parameters. The variables investigated in this study include density, bitumen/water proportions, degree of saturation and ambient temperature.

The limited information available in the literature on thermal properties of oil sands is presented in Chapter 2. A brief review on the thermal properties of the constituents of oil sands as well as those of granular and rock masses found near oil sands formations is presented in Appendix A. The inclusion of these thermal property data in the Appendix is mainly for reference purpose as the readers may find them useful. It also serves as a starting point for further research on the thermal properties of these relevant materials.

The one-dimensional heat conduction theory used for the current study is discussed in Chapter 3. Thermal property testing methods using both steady state and transient state techniques are mentioned. The transient state radial heat conduction theory forms the basis of the thermal testing apparatus devised for this study. Details of how the theory may be applied to thermal conductivity and thermal diffusivity determination are described extensively in this chapter.

Chapter 4 presents details of the laboratory testing assembly. This includes the steady state hot plate apparatus (used for comparison purpose), the newly devised transient state thermal test cell, as well as the necessary pieces of apparatus required to simulate *in situ* temperature and pressure conditions. Sample preparation and mounting procedures are also described here. The proposed thermal testing program for this study is outlined as well. Emphasis of the program is placed on the determination of thermal properties of quartz sands as well as remoulded and undisturbed oil sand specimens.

The results of laboratory tests are summarized in tables and figures in Chapter 5. Chapter 6 includes discussions on the experimental results as well as comparisons of the results with published data. The relative significance of the various factors that affect the thermal properties of oil sands is also discussed in this chapter. Based on the experimental findings, conclusions are drawn and are included in Chapter 7. Recommendations for future research are also outlined in the final chapter of this thesis.

A bibliography is given at the end of Chapter 7. The bibliography was compiled from an extensive literature search for relevant references relating to the topic of thermal property measurements on soil and rock materials. Instead of a list of references on the current thesis topic only, the inclusion of other relevant references in the bibliography may be valuable in future research in the area of thermal property testing of other deposits of oil sands, oil shales, as well as their overburden and interbedded strata.

Table 1.1 Factors Affecting Thermal Properties of Oil Sands

Factors	Thermal Conductivity	Thermal Diffusivity	Specific Heat
MATERIAL			
Mineral Grains	significant	significant	intermediate
Soil Structure (grain size distribution)	significant	significant	low
Density (porosity)	significant	significant	intermediate
SATURATION			
Bitumen/Water Proportions	uncertain	uncertain	intermediate
Degree of Fluid Saturation (Presence of Gas)	significant	significant	significant
UNIFORMITY			
Homogeneity	uncertain	uncertain	low
Isotropy	uncertain	uncertain	low
AMBIENT CONDITIONS			
Confining Pressure	uncertain	uncertain	low
Pore Fluid Pressure	low	low	low
Temperature	significant	significant	intermediate

2. LITERATURE REVIEW

2.1 Introduction

The literature review carried out for the current research generally covers three areas. As the first stage, a review of the open literature on laboratory equipment designs for thermal property testing is essential. Upon selection of the appropriate thermal testing apparatus, attention is directed to the gathering of enough information on theories and analytical methods that support the particular design. The third area of literature search then involves the collection of published data of thermal properties of different materials that will be used for comparisons with experimental results later.

Descriptions of the laboratory apparatus used in this study as well as the theoretical bases and analytical methods are included in the following two chapters. Reference materials relevant to the different parts are also quoted in the chapters and will not be repeated here. Therefore, this chapter on literature review will be devoted to the presentation of thermal property data of oil sands gathered for the current study. As part of the literature search, a brief review on the thermal properties of the constituents of oil sands and those of granular and rock masses is included in Appendix A. This additional information is provided for reference and future research purposes.

The literature search on the thermal property data of different soil and rock materials has been carried out as follows. Various key words relating to thermal properties and material types were used as input parameters to retrieve relevant abstracts from on line computer data bases. Following the identification of relevant citations, the corresponding papers or references were then collected. The *Tulsa* library and the *Alberta Oil Sands Information Centre* were the key sources of information.

2.2 Thermal Properties of Oil Sands

Although much work has been done on characterizing the general physical properties of oil sands, information on thermal properties of the deposits is rather limited in the literature. Most of the thermophysical properties of oil sands reported are based on experimental values obtained from disturbed or reconstituted samples. Elaborate attempts were made by some investigators to reconstitute test specimens to as close to their *in situ* states as possible. The effects of temperature on thermal properties of oil sands were also studied by some researchers.

Clark (1944) used a sample of bituminous sand from the Abasand Oils Limited quarry for thermal property evaluation. He measured thermal conductivity using a steady state line heat source technique. A thermos bottle was utilized for specific heat measurement. Results of Clark's thermophysical property testings are included in Table 2.1.

The thermal conductivity of unconsolidated oil sands have been studied extensively by Somerton and his colleagues at the University of California, Berkeley. A summary of their general findings is presented in a report by Somerton (1973). Thermal conductivities of the oil sands with various saturating fluids at different saturations were measured with a steady state thermal comparator apparatus. An oil sand specimen was made by punching out a 2-inch diameter disc from the centre of the original 5-in diameter core. The specimen was then carefully placed inside a holder. Thermophysical properties of unconsolidated extracted oil sands are tabulated in Table 2.2, and those of unextracted Kern River oil sands in Table 2.3. All samples were tested under an axial stress of 350 psi (2450 kPa) and at 125 °F (52 °C). Results of the mineral analysis and calculated solids conductivity of the oil sands are presented in Table 2.4. It must be stressed, however, that in the calculation of solids conductivity of the oil sands; an average conductivity value based on volume fractions of the solid constituents is assumed by the authors. This approach of approximating thermal conductivity of solids may be questionable. Nevertheless, it is not within the scope of this research ~~to~~ investigate the validity of this method of thermal conductivity approximation.

Karim and Hanafi (1981) studied the thermal conductivities of various natural and reconstituted Athabasca oil sand samples at temperatures ranging from

20 °C to 120 °C. The apparatus used was a coaxial type steady state thermal testing assembly. Bitumen contents were adjusted during the preparation of different remoulded samples. The findings are presented graphically in Figure 2.1. There is no mention of the degree of water saturations of the samples. The percentages given are for oil contents by mass of the sample only.

Cervenan, Vermeulen and Chute (1981) used a steady state hot plate apparatus for the determination of thermal conductivities of some reconstituted Athabasca oil sand samples at room temperature and pressure conditions. Specific heats of several specimens were established using a conductive electrical heating technique. Results of the experiments are tabulated in Tables 2.5 and 2.6. The dependence of thermal conductivity on water saturation is delineated by a curve shown in Figure 2.2.

Seki, Cheng and Fukusako (1981) have devised a transient state thermal testing apparatus for thermal property determination. Thermal conductivity and specific heat values of specimens from a disturbed medium grade Alberta oil sand sample were measured. From the ratios of thermal conductivity to heat capacity (the product of density and specific heat), thermal diffusivity values of the sample were derived. The variations of thermal conductivity, heat capacity and thermal diffusivity with temperature (15 °C to 480 °C) are depicted in Figure 2.3. It should be noted that the drastic drop of thermal conductivity (and subsequently the diffusivity) value at about 100 °C is due to vaporization of fluids in the specimen. There is no provision of a back fluid pore pressure system for the apparatus to prevent fluids from vaporizing at elevated temperatures.

Specific heats of oil sands from four major deposits in the United States and Canada have been studied by Rajeshwar, Jones and DuBow (1982). Differential scanning calorimetry was employed to measure specific heats. Physical properties of the oil sands and composition of the oil sand bitumen are listed in Table 2.7. Table 2.8 shows a comparison of the specific heats of raw oil sands and extracted bitumen of the four deposits. The same type of comparison is made for N.W. Asphalt Ridge oil sands (sample B) at temperatures from about 120 °C to 375 °C and is shown graphically in Figure 2.4.

Using a differential scanning calorimeter, Smith-Magowan, Skauge and Hepler (1982) measured the specific heats of Athabasca oil sands at temperatures ranging from 50 °C to 300 °C. Figure 2.5 displays the dependence of specific heat on temperature for a medium grade oil sand. The authors suggest that the specific heat of oil sand can be estimated rather accurately, within 5 %, by taking the weighted average of the specific heats of its components.

Thermal properties of Utah oil sands have been studied by Lindberg, Thomas and Christensen (1983). Specific heat and thermal conductivity values were determined using a controlled transient method. Samples discs of 10 cm diameter and 2.5 cm thickness were stacked up inside an insulated container for thermal testing. Specific heats of bitumen and sand constituents of oil sands are presented graphically in Figure 2.6. Table 2.9 summarizes the thermophysical properties of the oil sand samples tested by the authors.

Although the current study concentrates on the thermophysical properties of Athabasca oil sands, it may be worthwhile to cite a few reference papers that deal with thermal properties of oil shales. The experimental results obtained from this closely related area of oil shale research may be valuable in helping to explain the thermal behaviour of bituminous sands.

A great deal of work has been done by researchers at the Colorado State University on thermal property measurements on oil shales. DuBow (1977) measured the thermal and electrical conductivity of Green River oil shale for the U.S. Department of Energy. DuBow *et al* (1978) studied the effects of moisture and organic content on the thermophysical properties of the same shale. In a paper published in 1978, Wang, Rajeshwar and DuBow presented an analysis of the dependence of thermal transport parameters on organic content for the shale. Rajeshwar and DuBow (1979) discussed the thermophysical properties of Devonian shales. The specific heats of Colorado oil shales were studied by Jones, Rajeshwar and DuBow (1980) by means of a differential scanning calorimeter. Wang, Rajeshwar and DuBow (1980) investigated the dependence of thermal diffusivity on organic content for Green River oil shales. Practical applications of thermophysical property measurements in oil shale technology were discussed by Rajeshwar and DuBow (1981). Apart from university research, other research centre and private company individuals such as Tihen, Carpenter and Sohns (1968), and Prats and O'Brien (1975) have also studied the thermal conductivity and diffusivity of Green River oil shales. As noted from the results presented in the above references, both the thermal conductivity and diffusivity of oil shales generally decrease with increasing temperature as well as with increasing oil grade. Figure 2.7 typifies the variations of thermal conductivity of oil shales with temperature and oil grade.

Table 2.1 Thermophysical Properties of Athabasca Oil Sands from Clark (1944)

Thermal Conductivity

Oil sand sample % bitumen by mass	Sample condition	Thermal conductivity W/m °C
17.1	as-received	1.47
17.1	remoulded	1.13-1.34
11.7	remoulded	0.88
8.6	remoulded	1.00
3.0	remoulded	0.71

Grain Size Distribution

Percent retained on mesh			
#50	#80	#100	#200
0.1	3.4	25.1-25.6	95.6-96.8

Other Thermophysical Properties (as-received sample)

Specific heat	0.91 J/g °C
Porosity	39-40 %
Bitumen saturation	80-85 %
Water saturation	3.5-4.5%
Specific gravity	1.93-1.96

Table 2.2 Physical Properties of Dry Extracted Kern River Oil Sands from Somerton, Keese and Chu (1974)

Source	Depth ft	Permeability darcies	Porosity %	Thermal Conductivity W/m °C	Median Grain Size in	D_{90}/D_{10}
Kern River	575	1.06	31	0.446	0.0231	0.063
Kern River	598	-	42	0.381	0.0285	0.097
Kern River	598	2.94	37	0.381	0.0285	0.185
Midway-Sunset	949	2.55	45	0.358	0.0079	0.076
Midway-Sunset	955	0.59	42	0.376	0.0070	0.076
Huntington Beach	2460	2.05	38	0.341	0.0082	0.161
Huntington Beach	2460	2.26	40	0.348	0.0082	0.161
Huntington Beach	2460	2.33	41	0.358	0.0082	0.161
Huntington Beach	2460	1.86	43	0.339	0.0072	0.161
Bradley Canyon	2638	0.21	36	0.358	0.0072	0.100
Bradley Canyon	2768	0.79	41	0.384	0.0064	0.192
Bradley Canyon	2782	0.49	41	0.337	0.0057	0.103
Bradley Canyon	2796	0.34	38	0.348	0.0052	0.103

Table 2.3 Physical Properties of Kern River Oil Sands from Somerton, Keese and Chu (1974)

Depth ft	Porosity %	Bulk Density g/cm^3	Median Grain Size in	Saturations		Thermal Conductivity W/m °C
				Water %	Oil %	
374-380	30	2.05	0.033	51	23	1.78
	29	2.11		61	31	1.94
	30	2.11		60	27	1.94
	32	1.97		37	26	1.57
	33	1.95		18	22	1.47
	31	2.00		28	44	1.47
	31	2.07		50	32	1.87
	30	2.00		60	0	1.99
	29	2.11		81	0	2.22
	30	1.94		7	29	1.25
	28	2.15		60	26	1.99
	31	1.89		10	20	1.16
	28	1.86		0	0	0.62
	28	2.16		100	0	2.46
543-550	33	2.07	0.0164	34	64	1.59
	33	2.07		29	67	1.44
	33	2.07		37	62	1.56
	35	2.10		34	55	1.61
	33	2.08		33	61	1.56
	33	2.00		32	56	1.61
	30	2.07		29	46	1.57
	30	2.03		28	34	1.56
	35	1.94		8	53	1.09
	31	2.05		25	52	1.38
	31	2.07		77	0	2.27
	31	2.05		76	0	2.23
	33	2.03		78	0	2.11
	31	2.08		95	0	2.32
	32	1.79		0	0	0.52
	31	2.11		100	0	2.39
614-617	31	2.08	0.0116	46	44	1.63
	32	2.07		46	41	1.57
	35	2.00		37	43	1.49
	36	2.03		54	40	1.61
	32	2.02		38	46	1.56
	34	2.03		87	0	2.06
	33	1.87		7	32	0.97
	32	1.94		13	39	1.16
	32	1.87		5	25	1.02
	33	1.99		65	0	2.02
	30	2.03		71	0	2.27
	35	2.02		92	0	2.01
	34	1.95		68	0	1.96
	37	1.65		0	0	0.47
	34	2.07		100	0	2.08

Table 2.4 Volume Fractions of Constituents of Kern River Oil Sand from Somerton, Keese and Chu (1974)

Mineral	Fraction (n)	Thermal Conductivity (k), W/m °C	n x k
Quartz	0.34	4.45	1.513
Orthoclase	0.01	1.34	0.013
Plagioclase	0.21	1.24	0.260
Kaolinite-Sericite	0.25	1.60	0.400
Chlorite	0.07	2.84	0.197
Hornblende	0.04	1.78	0.072
Sphene	0.02	1.35	0.027
Epidote	0.02	1.51	0.030
Others	0.04	1.35	0.054
Total	1.00		2.566

Table 2.5 Thermal Conductivity of Reconstituted Athabasca Oil Sands from Cervenan, Vermeulen and Chute (1981)

Percent by Mass			Density	Porosity	Pore Saturation		Thermal Conductivity W/m °C	
					Water	Bitumen		
Sand	Bitumen	Water	g/cm³	%	%	%	Measured	Calculated
				SUNCOR-upper bench				
87.9	8.0	4.1	1.89	37.8	20.7	39.4	1.59	1.74
87.9	7.8	4.3	1.81	40.0	19.5	32.7	1.67	1.66
87.9	7.8	4.3	1.92	36.5	22.7	37.8	1.61	1.84
87.9	7.9	4.2	1.90	37.0	21.5	37.8	1.80	1.82
87.9	8.1	4.1	1.98	34.3	23.4	43.1	1.80*	1.91
				SUNCOR-middle bench				
84.3	13.8	1.9	1.84	41.4	8.6	56.8	1.50	1.19
85.2	12.9	1.9	1.83	41.2	8.4	53.0	1.47	1.19
84.8	13.1	2.1	1.92	38.4	10.7	60.6	1.42	1.36
84.8	13.1	2.1	1.89	39.7	10.1	57.5	1.52	1.30
85.3	13.1	1.6	1.89	39.2	7.5	58.5	1.72	1.19
76.9	12.0	11.1	1.86	46.2	44.7	44.7	1.90	2.18
76.9	12.0	11.1	1.85	46.5	44.2	44.2	1.98	2.16
85.3	13.9	0.8	1.92	38.2	4.1	64.6	1.31*	1.00
				SUNCOR-lower bench				
84.0	14.3	1.7	1.90	39.7	8.1	63.9	1.48	1.21
88.6	10.1	1.3	1.89	36.7	6.6	48.8	1.70	1.19
83.8	14.7	1.5	1.94	38.8	7.3	68.1	1.59	1.19
83.5	15.1	1.4	1.96	38.3	7.3	71.6	1.67	1.20
83.5	14.5	2.0	1.94	39.0	9.7	66.7	1.56	1.30
84.2	15.6	0.17	1.95	38.0	0.85	74.2	1.32	0.68
83.3	15.0	1.7	1.95	38.6	8.6	70.4	1.44*	1.26
83.6	15.2	1.2	1.94	38.8	6.1	70.2	1.35	1.12
				Extracted Sand				
85.0	0	15.0	1.78	42.9	62.2	0	2.39	2.60
95.8	0	3.7	1.54	44.5	12.7	0	1.24	1.31
99.0	0	1.0	1.47	45.1	3.3	0	0.80	0.78

*Measured by coaxial cell.

Table 2.6 Specific Heat of Reconstituted Athabasca Oil Sands from Cervenan, Vermeulen and Chute (1981)

Percent by Mass			Density	Temperature Range of Heating	Specific Heat, J/g °C	
Sand	Bitumen	Water	g/cm³	°C	Measured	Calculated
83.8	14.8	1.5	1.86	24–29	0.91	0.92
83.6	14.8	1.6	1.90	25–29	0.90	0.92
76.9	12.0	11.1	1.86	23–26	1.22	1.23
76.9	12.0	11.1	1.86	23–43	1.17	1.23
76.9	12.0	11.1	1.80	45–51	1.20	1.23
76.9	12.0	11.1	1.80	70–73	1.23	1.23
83.5	15.1	1.4	1.91	23–29	0.96	0.92
83.5	15.1	1.4	1.91	71–74	1.02	0.92
96.0	0	4.0	1.62	23–27	0.85	0.90
98.0	0	2.0	1.46	23–27	0.84	0.83

Table 2.7 Properties of Oil Sands and Composition of Oil Sand Bitumen from Rajeshwar, Jones and DuBow (1982)

	Oil Sand				
Property	Athabasca	N.W.Asphalt Ridge A	P.R.Spring	N.W.Asphalt Ridge B	Circle Cliffs
Elemental analyses					
Carbon, wt%	82.13	84.15	78.49	-	77.02
Hydrogen, wt%	10.32	11.18	9.89	-	9.12
Nitrogen, wt%	0.44	1.12	1.15	-	0.49
Sulphur, wt%	5.73	0.69	0.65	-	5.72
Oxygen, wt%	0.92	0.77	5.84	-	4.73
Specific gravity, g/cm^3	2.05	1.97	1.83	2.11	2.27
Ash yield, wt%	0.40	0.26	4.59	-	7.52
Mineral CO_2, wt%	0.02	0.02	0.02	-	0.03
Bitumen content, wt%	14.39	13.08	11.22	7.84	4.08
Moisture content, wt%	1.14	0.22	0.19	0.10	0.24

Table 2.8 Comparison of Specific Heats for Raw Oil Sands and Extracted Bitumen by Rajeshwar, Jones and DuBow (1982)

	c, J/g °C	
Oil sand	Raw oil sand	Extracted bitumen
N.W. Asphalt Ridge (sample A)	0.745	2.27
P.R. Spring	1.00	1.75
N.W. Asphalt Ridge (sample B)	0.950	2.21
Circle Cliffs	0.745	1.53
Athabasca	0.670	1.96

N.B. Reference temperature is 125°C
Nominal mean deviation in measured values is ±5%

Table 2.9 Properties of Asphalt Ridge Oil Sands from Lindberg, Thomas and Christensen (1983)

Sample	Density, g/cm^3		Porosity, %		Permeability, millidarcies		Weight % Oil	Water Saturation %	Measured Thermal Conductivity W/m °C
	Saturated	Extracted	Saturated	Extracted	Saturated	Extracted			
1	2.305	2.152	1.29	18.33	2.3	231.3	6.61	3.32	1.80
2	2.058	1.791	6.59	32.40	12.5	462.0	12.82	1.43	1.39
3	1.893	1.830	7.46	26.20	7.7	56.3	3.25	2.49	1.30
4	2.075	1.820	3.22	28.60	6.4	400.0	12.09	7.71	1.39
5	2.069	1.804	0.46	41.27	13.2	1599.0	12.66	5.57	1.22
6	2.056	1.845	7.15	29.33	8.5	443.0	10.10	6.49	1.35
7	1.867	1.795	24.04	31.47	404.0	479.0	3.62	0.27	1.32
8	2.013	1.875	8.69	25.01	13.5	156.9	6.71	9.76	1.60

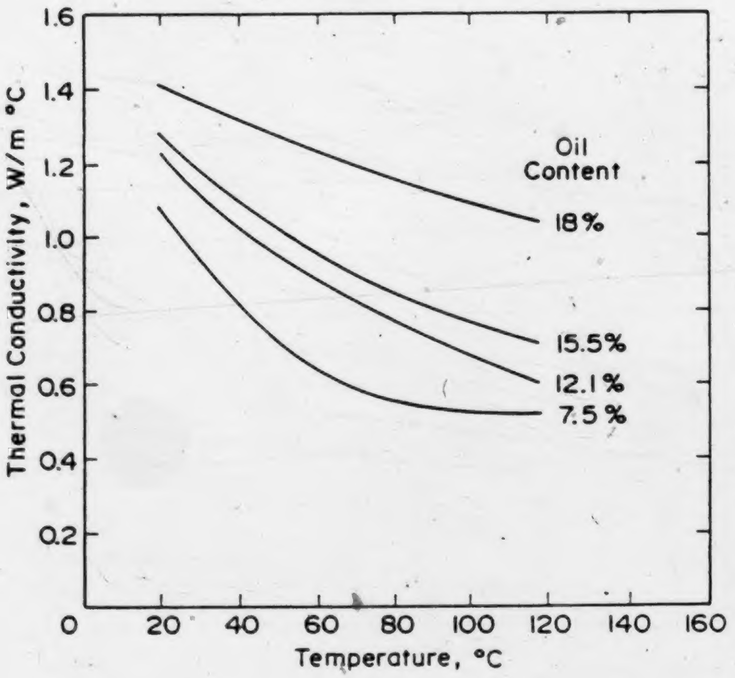
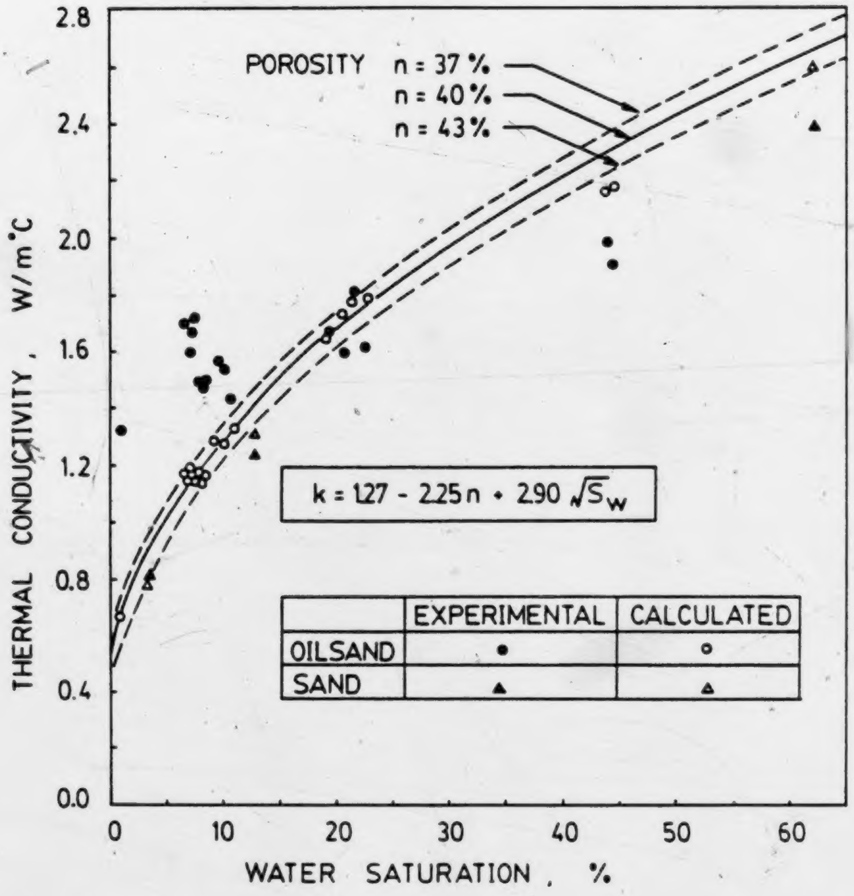
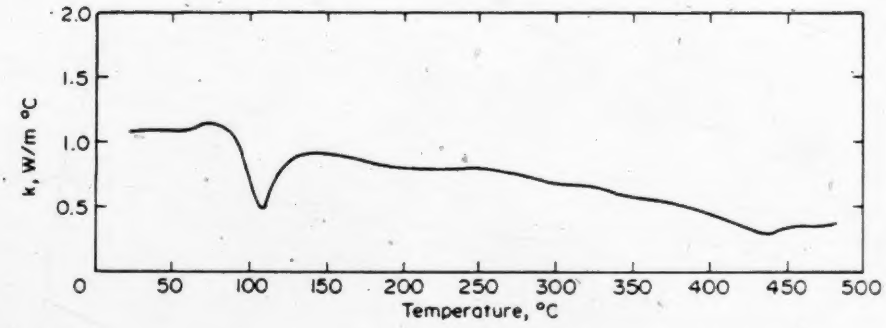


Figure 2.1 Thermal Conductivity of Athabasca Oil Sands from Karim and Hanafi (1981)

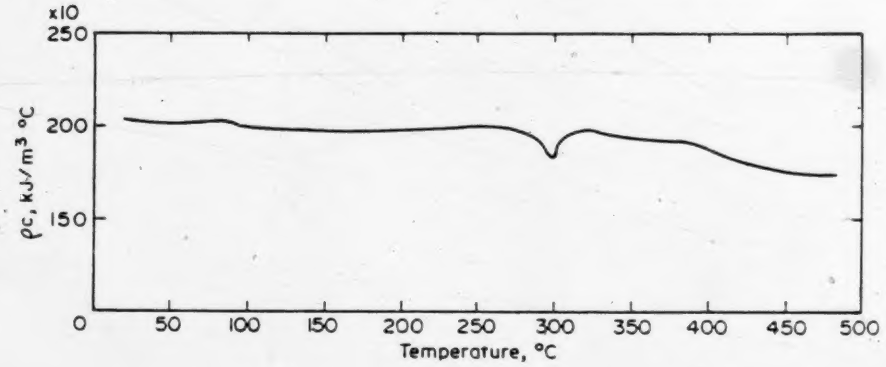


	EXPERIMENTAL	CALCULATED
OILSAND	●	○
SAND	▲	△

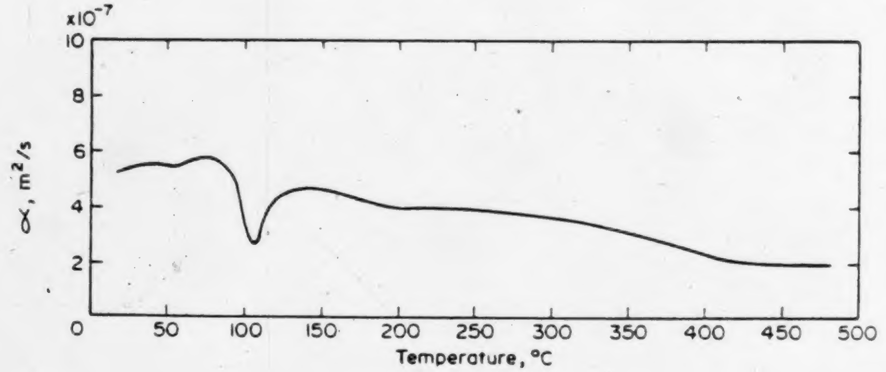
Figure 2.2 Correlation of Thermal Conductivity with Water Saturation of Athabasca Oil Sands by Cervenan, Vermeulen and Chute (1981)



Thermal Conductivity



Heat Capacity



Thermal Diffusivity

Figure 2.3 Thermal Properties of Athabasca Oil Sands from Seki, Cheng and Fukusako (1981)

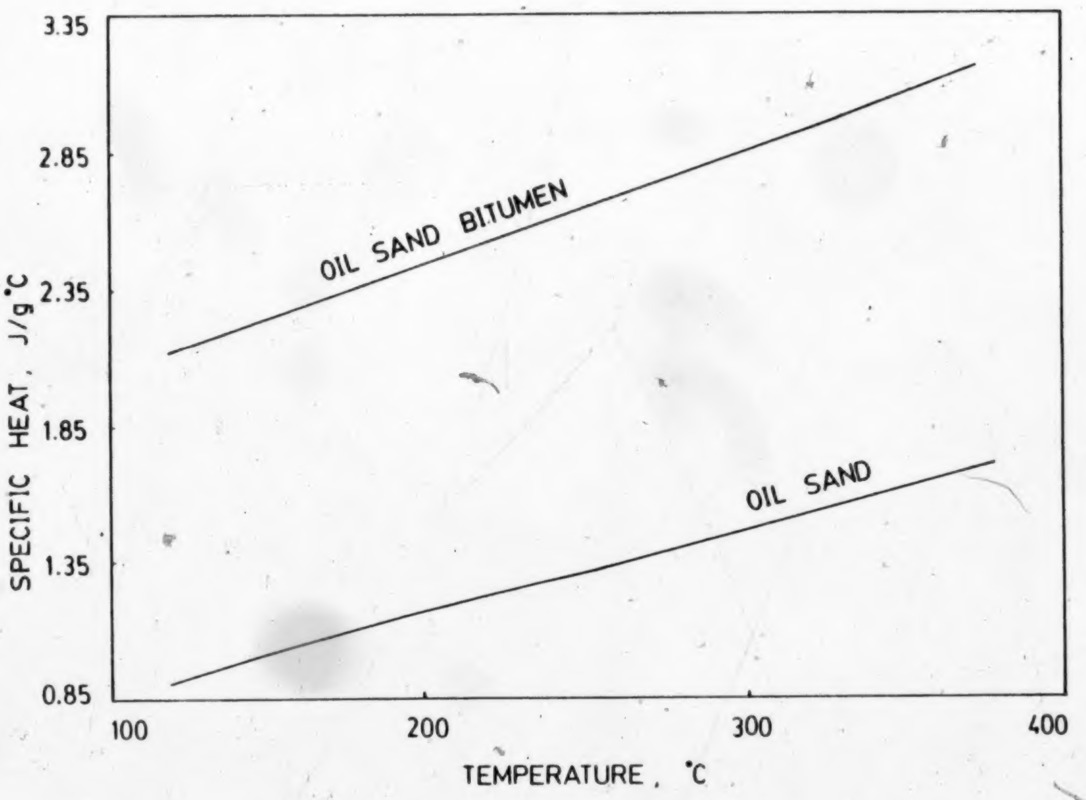


Figure 2.4 Comparison of Specific Heats of Asphalt Ridge Oil Sands and Oil Sand Bitumen by Rajeshwar, Jones and DuBow (1982)

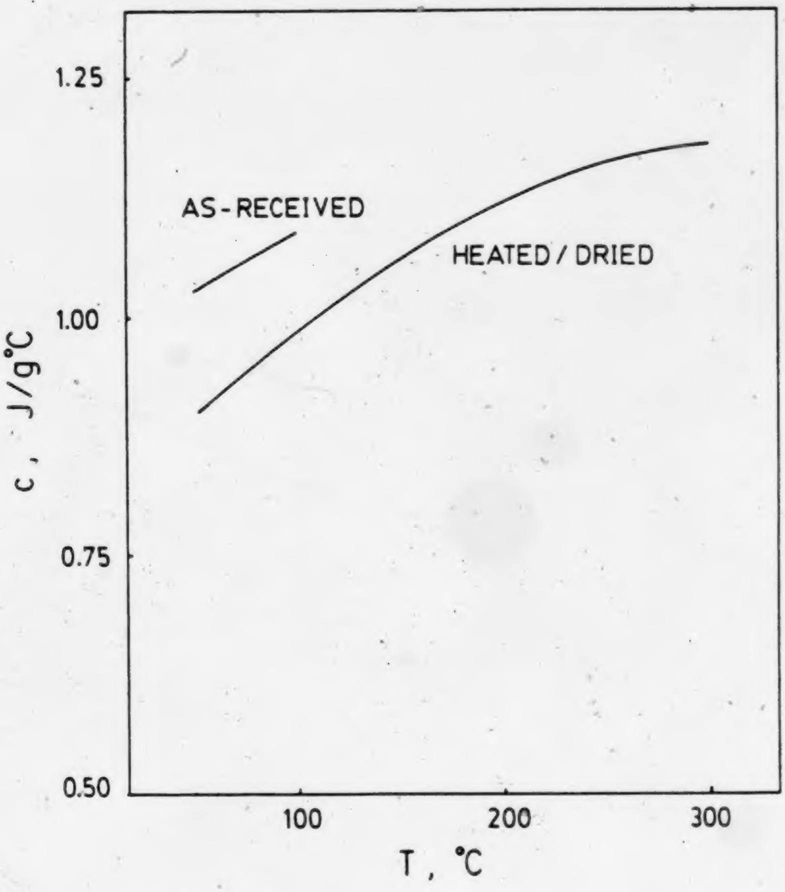


Figure 2.5 Specific Heat of Athabasca Oil Sands from Smith-Magowan, Skauge and Hepler (1982)

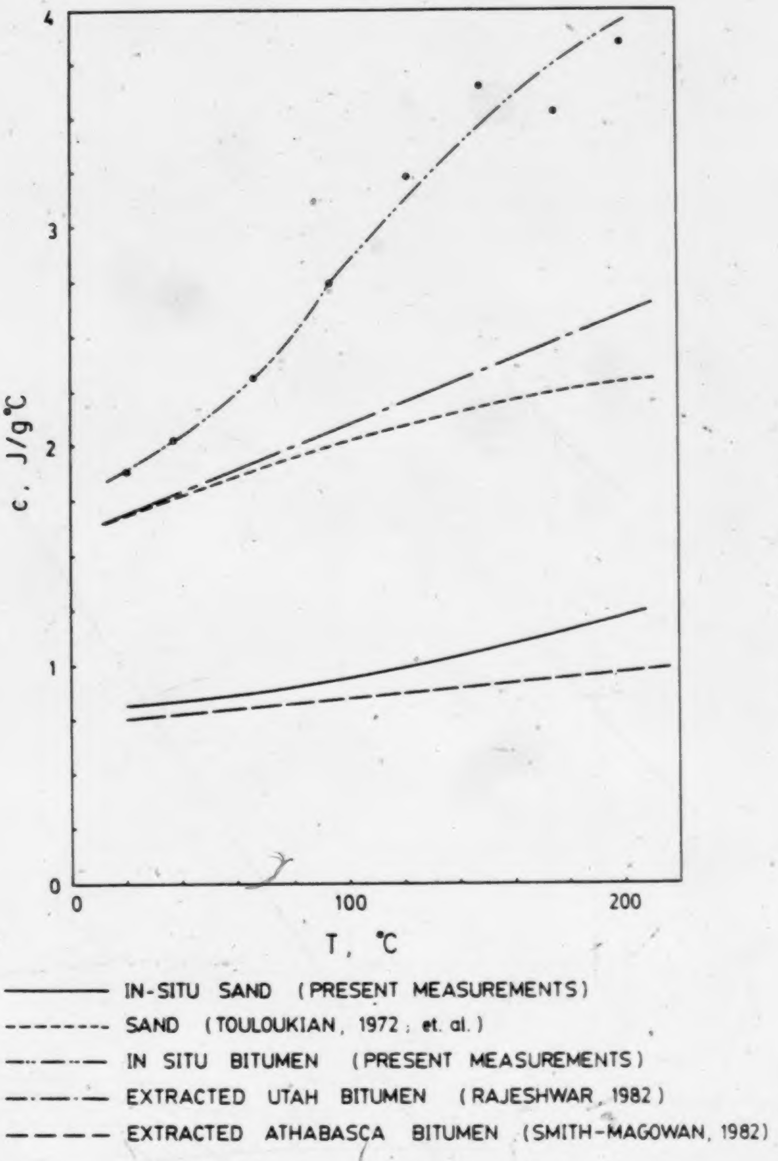


Figure 2.6 Specific Heats of Bitumen and Sand Constituents of Asphalt Ridge Oil Sands from Lindberg, Thomas and Christensen (1983)

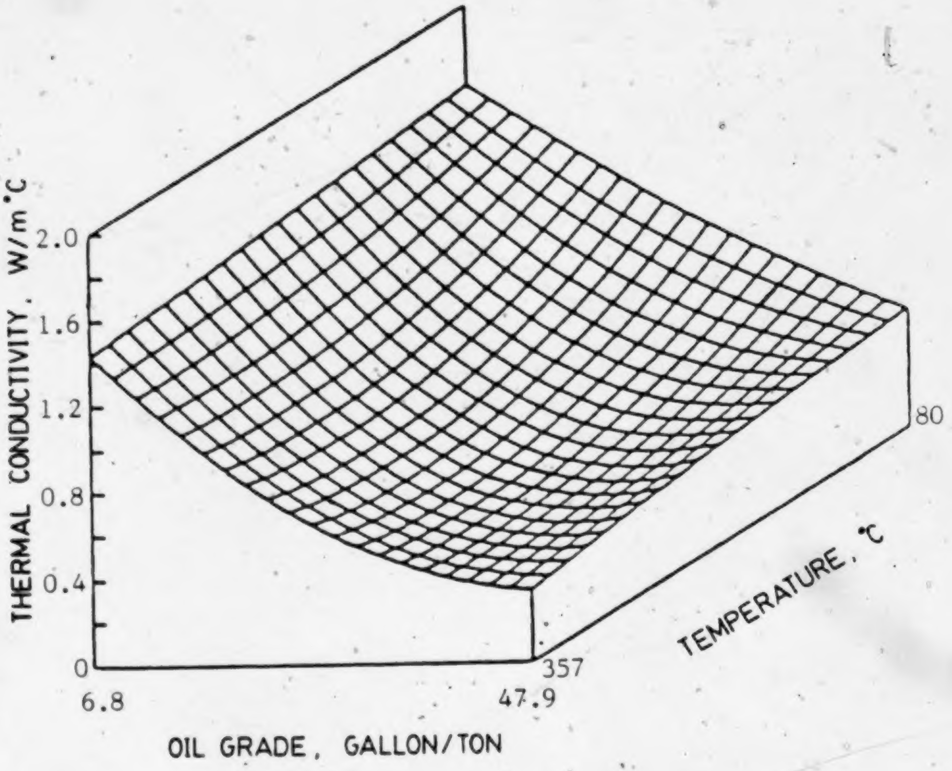


Figure 2.7 Typical Contour Diagram showing Variations of Thermal Conductivity with Temperature and Oil Grade from DuBow et al (1978)

3. THERMAL TEST APPARATUS AND METHODS OF ANALYSIS

3.1 Introduction

Thermal property testing methods are generally divided into two categories, namely, steady state and transient state techniques. Prior to the designing of a thermal test apparatus and test procedures that are most suited for the objectives of the thesis, a review of the different pieces of apparatus and the methods of analysis employed by other researchers is essential. The advantages and disadvantages of the various thermal testing devices are discussed. Special attention is given to the applicabilities of steady state or transient state techniques to thermal testing of undisturbed oil sand cores at elevated pressures and temperatures.

Based on the following findings, it was decided to use the transient state method of thermal testing. Therefore, this method is covered in some detail in this chapter.

3.2 Steady State Thermal Testing

3.2.1 General Theory

Steady state one-dimensional linear heat conduction in a uniform homogeneous medium is governed by the following Laplace's equation:

$$\frac{\partial^2 T}{\partial Z^2} = 0 \qquad 3.1$$

where T (°C) is the temperature at any point Z (m) from the origin.

Assuming that the temperature at $Z = L_1$ is T_1 and at some other location, $Z = L_2$, T_2 (Figure 3.1), the solution to equation 3.1 is:

$$T = \frac{T_2 - T_1}{L_2 - L_1} Z + T_1 \qquad 3.2$$

The rate of heat flow, q, is proportional to the thermal gradient, $\partial T/\partial Z$, across the two points (at $Z = L_1$ and $Z = L_2$) as well as to the cross-sectional area, A_x, normal to the heat flow direction. Heat flows from an area of high temperature to another area of lower temperature (Figure 3.2).

Thus:

$$q = - k \frac{\partial T}{\partial Z} A_x$$

or

$$q = - k \frac{T_2 - T_1}{L_2 - L_1} A_x \qquad 3.3$$

where the units may be:
q (W)
k (W/m °C)
T (°C)
A_x (m^2)
L (m)

The constant of proportionality, k, is defined as the thermal conductivity of the medium.

3.2.2 Standard Hot Plate Apparatus

The ASTM standard test method (ASTM, 1982) for steady state thermal transmission properties of a material employs a guarded hot plate assembly (Figure 3.3). The experimental set-up and testing procedures are well known. Basically, the set-up should have a constant heat generating source, such as a metallic hot plate with a dc power supply, at one surface of the test specimen and a constant cold curface maintained at the other. The outer boundaries of the heating and cooling units together with the specimen are well insulated so that one-dimensional heat flow is ensured across the bulk of the sample. Thermocouples are used to monitor temperatures at both surfaces of the specimen during the test until it is certain that thermal equilibrium of the system is reached. With flow rate of heat , q, specimen thickness, $L_2 - L_1$, cross-sectional area of the specimen, A_x, and steady state temperature differential, $T_2 - T_1$, known, the thermal conductivity of the specimen can be evaluated from equation 3.3.

3.2.3 Thermal Comparator or Divided Bar Apparatus

In order to calibrate the standard hot plate apparatus, a steady state test on a standard material of known thermal conductivity is generally carried out prior to the testing of a specimen of unknown conductivity. The use of a thermal comparator apparatus eliminates this calibration procedure. A schematic drawing of an example of the comparator assembly is shown in Figure 3.4 and Figure 3.5. In this set-up, the sample of unknown thermal conductivity is sandwiched between two standard reference samples of known conductivity. A thermal gradient across the stack of samples is created by the upper stack heater and the lower heat sink. Temperatures across the sample and the standard material are measured when thermal equilibrium of the system is achieved. Since the rate of heat flow in the stack arrangement is constant, the thermal gradients across the samples will vary according to their respective thermal conductivities. With the thermal gradients measured and the conductivity of the reference material known, the thermal conductivity of the test specimen may readily be determined by equating the rate of heat flow (equation 3.3) in the specimen with that across the reference material. Pyroceram glass ceramic code 9609 or fused quartz is generally used as the standard reference material.

The divided bar apparatus employs the same technique as that used by the thermal comparator except that two bars of a standard material (e.g. brass) are used to sandwich the test specimen. The metal bars are taken as reference for thermal conductivity evaluation. An example of the divided bar assembly is included in Figure 3.6. Various modifications to this apparatus have been made by many researchers, but the designs will not be discussed here..

3.2.4 Coaxial Thermal Testing Apparatus

The steady state coaxial or cylindrical thermal testing apparatus employs the theory of one-dimensional radial heat flow. Figure 3.7 depicts an example of the apparatus. A constant heat source is generated along the inner core of the cylinder. The external surface temperature of the assembly is maintained by a constant-temperature fluid bath. Thermal equilibrium is allowed to be established as heat moves radially outwards in a steady state condition. The steady state one-dimensional radial heat flow theory will not be detailed here, but the solution can readily be derived by applying the new boundary conditions and a cylindrical coordinate system to the governing differential equation (3.1).

3.2.5 Advantages and Disadvantages of Steady State Thermal Testing

The simplicity of the steady state one-dimensional linear heat conduction theory gives the standard hot plate method of thermal conductivity testing its attractiveness. The method has been widely used in thermal conductivity testing of uniform homogeneous materials. If the apparatus is properly insulated and if the average sample temperature is close to the ambient temperature, the amount of heat loss to the environment is negligible and the accuracy of the result is high.

The major source of error in thermal conductivity testing by the hot plate method is thermal contact resistance at the specimen and hot/cold unit interfaces.

ASTM (1982) states the criteria in selecting a proper specimen that the thermal resistance of the specimen must be sufficiently independent of its area, of where the specimen is chosen in the sample, and of the temperature differential across the specimen. For a flat slab specimen, the thermal resistance, R (m^2 °C/W), must be proportional to the thickness, l (m). That is:

$$R = \frac{l}{k} \qquad 3.4$$

where k (W/m °C) is the thermal conductivity.

Therefore, a plot of thermal resistance versus specimen thickness yields a straight line and should pass through the origin. However, Cervenan, Vermeulen and Chute (1981) have shown, from their thermal testings on reconstituted oil sands, that there may be a finite intercept on the thermal resistance axis at zero specimen thickness on the plot (Figure 3.8). The intercept is an indication that thermal contact resistances at the hot and cold surfaces are not negligible. Assuming that thermal contact resistances at the two interfaces are equal, as the materials and confining stresses at both faces are the same, equation 3.3 may be modified to include thermal contact resistance as follows: (Kutateladze and Borishanskii, 1966)

$$\frac{\Delta T}{q_s} = \frac{2}{H} + \frac{l}{k} \qquad 3.5$$

where: ΔT = Temperature difference across the specimen (°C)

l = Specimen thickness (m)

k = Thermal conductivity of specimen (W/m °C)

H = Coefficient of heat transfer at sample/plate interface (W/m^2 °C)
(a measure of thermal contact resistance)

$q_s = q/A_x$ = Rate of heat flow per unit area across the specimen (W/m^2)

Equation 3.5 suggests a linear relationship between $\Delta T/q_s$ and l, with 2/H as the intercept and 1/k as the slope. In order to establish the thermal conductivity value of a material, it is therefore required that specimens of different thicknesses be tested and the results plotted if the effects of thermal contact resistance is to be accounted for. This quest for better accuracy in thermal conductivity leads to a trade-off of experimental time and cost. Since at least three points may be required to approximate a linear relationship properly, three or more tests with similar specimens of different thicknesses will be needed to establish only one thermal conductivity value.

As noted by the ASTM (1982) standard for the guarded hot plate test, the test specimen as well as the material should be homogeneous. If the specimen is moist or saturated with a fluid, moisture redistribution may take place during the test thus rendering the specimen an apparent thermal non-homogeneity. Many investigators, such as Hooper and Lepper (1950), Vos (1955), Woodside and Messmer (1961), recognize the fact that the standard hot plate test is only good for testing dry and homogeneous materials. To study the more complex problem of the combined effects of moisture migration and heat flow in a medium, one may refer to reference papers by Hutcheson and Paxton (1952), Philip and de Vries (1957), Woodside and Kuzmak (1958), de Vries (1958), Woodside and Cliffe (1959), Winterkorn (1960), Su and Somerton (1979), and other reference materials on the subject.

Another disadvantage of using the hot plate method for testing saturated samples is the possible dominating effect of convection, especially at high temperatures. Furthermore, an undesirably long time is required for the hot plate assembly to reach both moisture and thermal equilibrium. ASTM (1982) recommends the use of separate apparatus for thermal conductivity testing for low and high temperatures. This means that at least two hot plate test set-ups, one for low temperature testing and the other high temperature, are required.

As fluids will vaporize at or beyond their saturation pressures, a well designed thermal conductivity test apparatus should include a back pore fluid pressure system to maintain gas and vapor in solution if high temperature testing is required. The standard hot plate set-up is limited to near room temperature and pressure testing. Investigators such as Boulant, Langlais and Klarsfeld (1981) have devised a guarded hot plate apparatus for high temperature thermal material property testing. ASTM (1982) also recommends a laboratory set-up of the hot plate apparatus for testing at high temperatures. However, there appears to be no provision for a back pore fluid pressure system to avoid vaporization of fluids in the sample chamber. A steady state comparator apparatus which allows for axial loading and back pore fluid pressure applications is described in detail in Anand's (1971) thesis. The apparatus is capable of being used at elevated temperatures and pressures. This improvement of the steady state thermal testing method is also presented in a paper by Anand, Somerton and Gomaa (1973).

Kersten (1949) used a steady state coaxial assembly for the determination of thermal conductivity of different soil types. More or less the same type of set-up was employed by Karim and Hanafi (1981) to estimate the thermal conductivity of Athabasca oil sands. Flynn and Watson (1969) have designed a coaxial steady state thermal conductivity test apparatus for high temperature testing on soil samples up to 1600 °C. The cylindrical symmetry of a coaxial apparatus is advantageous in preventing heat losses, particularly at elevated temperatures. Flynn and Watson also considered thermal contact resistance in their derivation of the steady state one-dimensional radial heat flow theory. Since the authors were trying to simulate the conditions of a nuclear power supply after re-entry impact burial in earth, they maintained the external heat sink at ambient temperature and increased the heat source along the central axis to the desired temperature. The ambient temperature was controlled by circulating water in the external brass shell. The coaxial apparatus could have been designed to incorporate a back pore pressure system, but presumably the authors' test cell was able to withstand the vapor and gas pressure generated upon heating of the sample.

A coaxial thermal property testing apparatus which allows pore fluid drainage (thus back pore pressure application) has been devised by Abey *et al* (1982). The thermal conductivity value of the specimen is obtained by one-dimensional steady state testing. The apparatus is capable of testing under a pressure up to 200 MPa and temperature up to 750 K and thus better simulates *in situ* conditions.

Although the coaxial set-up and the thermal comparator (or divided bar) apparatus are far more versatile in practice than the standard hot plate apparatus, the problem of uneven moisture redistribution and convection are still predominant in steady state testing. Furthermore, the difficulty of maintaining such a high temperature and pressure system is great, not to mention the necessary design of a good safety system.

Other criticisms on the hot plate apparatus point to the fact that it is complicated, not portable (a cooling fluid bath is usually required), and that it is difficult to obtain structurally undisturbed soil specimens in a size and shape suitable for the set-up.

Recognizing the many drawbacks and limitations of steady state thermal testing, many investigators are favoring transient state testing techniques that require shorter test times. The most commonly used method is a line heat source technique whereby a cylindrical sample is housed inside a jacket or container with a probe heater along the central axis. The probe is heated up by a constant power supply at the start of the test. The temperature rise with time is monitored by a thermocouple generally attached to mid-height of the probe. From the time-temperature record, the thermal conductivity of the specimen can be evaluated.

From the geotechnical engineering point of view, the laboratory testing of undisturbed soil/rock samples, as opposed to remoulded or reconstituted samples, under simulated *in situ* pressure and temperature conditions should give better and more representative results that may be used in the field. Since the only way to acquire undisturbed deep underground samples is by drilling, the sizes of the samples are limited. The thermal comparator or divided bar apparatus is a good modification to the standard hot plate apparatus for steady state thermal testing of intact soil/rock specimens. Sample discs of about 25 mm to 50 mm diameter may be trimmed from cores recovered from the field. However, the inevitable effect of convection and moisture redistribution, when testng partially or fully saturated samples under steady state conditions, poses some concern of the applicability of the measured thermal conductivity value to transient state heat transfer problems under actual field conditions.

Considering the aforementioned factors as well as the potential drawbacks of steady state thermal property testing, it appears more reasonable to use the transient state method for testing of undisturbed soil/rock samples at elevated pressures and temperatures.

3.3 Transient State Thermal Testing

3.3.1 Thermal Conductivity

3.3.1.1 General Theory

The partial differential equation that governs one-dimensional radial heat flow in an infinite homogeneous medium may be written as follows:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad 3.6$$

where: T = Temperature, a function of r and t (°C)

r = Radial distance (m)

t = Time (s)

α = Thermal diffusivity of the medium (m^2/s)

Depending on the boundary conditions imposed, equation 3.6 may yield solutions which are useful in the determination of the thermal conductivity and diffusivity of a material.

Before proceeding to the discussions of the appropriate solutions, one should note the following relationship:

$$\alpha = \frac{k}{\rho\ c} \qquad 3.7$$

where: k = Thermal conductivity (W/m °C)
α = Thermal diffusivity (m^2/s)
ρ = Density (kg/m^3)
c = Specific heat (J/kg °C)

Since the thermal conductivity and the thermal diffusivity of a material can be established experimentally and that the density is a measurable quantity, the specific heat of the material can be calculated from equation 3.7.

The transient state line source technique of thermal conductivity determination generally assumes the following set of boundary conditions (Figure 3.9):

1. Zero initial temperature throughout the medium.
2. Continuous heat source of strength, q_l, supplied instantaneously at the centre line at time, t, greater than zero.

The solution of equation 3.6 for this set of boundary conditions can be obtained from Carslaw and Jaeger (1959) and is stated as follows:

$$T = - \frac{q_l}{4\pi k} \text{Ei} \left(- \frac{r^2}{4\alpha t} \right) \qquad 3.8$$

where: T = Temperature, a function of r and t (°C)

q_l = Power input per unit length of line source (W/m)

k = Thermal conductivity of the medium (W/m °C)

α = Thermal diffusivity of the medium (m^2/s)

r = Radial distance from line source (m)

t = Time from start of power input (s)

and the exponential integral, $-Ei(-x)$, is defined as follows:

$$-Ei(-x) = \int_x^\infty \frac{e^{-u}}{u}\,du \qquad (x>0)$$

or

$$-Ei(-x) = -\dot{\gamma} - \ln x - \sum_{n=1}^{\infty} \frac{(-x)^n}{n.n!} \qquad 3.9$$

where: $\dot{\gamma}$ = 0.57722 (Euler's constant)

A plot of the exponential integral is delineated in Figure 3.10. The transient state thermal conductivity probe test assembly used in the current research is shown in Figure 3.11.

If the $r^2/4\alpha t$ term of equation 3.8 is small, the exponential integral may be approximated by the first two terms of equation 3.9 only:

$$T = \frac{q_l}{4\pi k} \left(\ln \frac{4\alpha t}{r^2} - \gamma \right) \qquad 3.10$$

Nix *et al* (1967) have calculated that for $r^2/4\alpha t < (0.16)^2$, the approximation is accurate to better than 1 %. By experimentally arranging the radial distance of the temperature sensing device and the time of testing, the $r^2/4\alpha t$ term can be minimized for a material of a specific thermal diffusivity value. This is the reason why most investigators prefer putting the temperature sensing device at or near the probe surface so that the approximation of equation 3.10 becomes valid.

If the difference in temperature at two separate times of measurement is taken, equation 3.10 will yield:

$$T_2 - T_1 = \frac{q_l}{4\pi k} \ln \frac{t_2}{t_1} \qquad 3.11$$

It is of interest to note that equation 3.11 is independent of thermal diffusivity, α. The equation indicates a linear relationship between temperature and the natural logarithm of time. Therefore, thermal conductivity can ideally be calculated from the slope of a temperature versus natural logarithm of time plot if the power input per unit length, q_l, is known.

However, typical plots of the temperature and natural logarithm of time relationship generally have shapes like the ones delineated by Wechsler (1966) in Figure 3.12. As recognized by many researchers, the curved portion of the experimental plots in region A is due to initial lag effects. The finite probe radius, the thermal properties of the probe, the temperature sensing device and the surrounding medium, as well as the thermal contact resistance between the probe and the medium together attribute to the initial curvature of the plots. The linear portion of the curve obtained by a well designed probe in region B is used for the evaluation of thermal conductivity. At larger times, in region C, the experimental plots start to bend again. Wechsler (1966) suggests that this is due to the loss of heat axially along the probe and/or the effects of finite sample size. If the curve concaves up in region C, the deviation may be due to sample boundary effects. If the curve concaves down, as in most cases, the deviation may be due to a combination of or one of the two above-mentioned effects.

3.3.1.2 Probable Errors and Justifications

It has been widely accepted that there are departures from the ideal line source conditions that may affect the thermal conductivity test results. The probable causes of error may be summarized as follows:

1. Finite dimensions of the thermal conductivity probe heater.
2. Variation in the resistance of the heating element of the probe with temperature.
3. Finite dimensions of the test specimen.
4. Heat conduction along the heater and the thermocouple.
5. Thermal contact resistance at the interface between probe and external medium.
6. Heat transfer by radiation and/or convection.

To minimize the first two errors, many researchers recommend the use of a thin probe heater with large length to diameter ratio and a heating element of low temperature coefficient of thermal resistance. However, Hooper and Allcut (1952) and Woodside (1958) point out the drawback of designing too thin a probe that may create undesirably high temperature and consequently moisture gradients near the probe, when moist samples are tested. Partial drying and moisture migration in the test specimen may affect the results. To compromise the two contradicting views, one should select a probe with an adequate length to diameter ratio such that a line source can be approximately simulated while the probe radius is not too small to create extremely high thermal gradients near its surface. In fact, Blackwell (1954, 1956) has proposed criteria for proper probe dimensions to avoid axial flow error as well as to ensure radial flow at least near the centre of the cylindrical sample.

If the testing period is short enough that the heat front never reaches the sample surface, the finite sample can be treated as infinite in extent. Together with proper design of the probe and a small power input to minimize thermal gradient across the ends of the sample, error 3 can practically be eliminated. Wechsler (1966) has proposed a criterion for sample radius to minimize the amount of heat reaching the sample boundary. This will be discussed in the following chapter.

Error 4 has been accounted for in the design of the probe according to Blackwell's (1954, 1956) recommendations. End heat losses should be small if the sample is well insulated at the ends.

Thermal contact resistance is generally assumed to be negligible when testing dense samples closely packed around the probe heater. This assumption is particularly justified when the test specimen is fully saturated with fluid which forms a uniform conducting medium around the probe. Van der Held and van Drunen (1949) also recommend the use of lower power input to minimize contact resistance across the probe surface.

Lentz (1952) has performed conductivity tests with the heater placed vertically as well as horizontally in a moist homogeneous isotropic medium. The lack of significant difference in his results suggests that the effect of convective heat flow is negligible for short-duration thermal conductivity testing. Anand (1971) suggests that convection is negligible for moderate size of sample pores. Vos (1955) mentions the fact that contribution of radiation to the apparent thermal conductivity is important for testing at high temperatures. The actual thermal conductivity of a material should be smaller if radiation effect is excluded. However, Anand (1971) states that radiation should be neglected at temperatures below 900 °F (480 °C). Sibbitt, Dodson and Tester (1979) agree that the contribution of radiation to thermal conductivity is usually negligible for temperatures below 800 K (527 °C). One should treat the apparent conductivity so measured as the sum of the true conductivity and the radiation conductivity instead of trying to single out the radiation effect. Therefore, error 6 is actually not a problem as radiation occurs in practice as well as in the laboratory test. Van der Held's papers (1953, 1954, 1956) and other references may be consulted for the effect of radiation on the conduction of heat.

3.3.1.3 Methods of Analysis

Previous Work

To account for the heat production period of the heater and the truncation error of higher order terms in the exponential integral (equation 3.9), van der Held and van Drunen (1949) devised a time correction factor, t_0, which can be determined by noting the time-axis intercept from a plot of time, t, versus dt/dT (Figure 3.13). The established t_0 value is then subtracted from each observed time. Equation 3.11 is thus modified to the following form:

$$T_2 - T_1 = \frac{q_i}{4\pi k} \ln \frac{t_2 - t_0}{t_1 - t_0} \qquad 3.12$$

With the newly corrected time scale, temperature readings are plotted against ln t to determine thermal conductivity as discussed in the previous section. It is believed that the re-plotting of the temperature record on a corrected ln t scale may linearize the initially curved plot from the uncorrected data.

The method of introducing a time correction is rather simple and has been widely used by many researchers, namely, Hooper and Lepper (1950), Lentz (1952), Woodside (1958), and Nix *et al* (1968).

However, Lentz (1952) admits that the correction is only an approximation to account for the departure from the ideal line source theory. Error in the calculated value of thermal conductivity appears to increase with increasing error in t_o. When the diameter of the probe heater is too large or the sample density too low, the thermal conductivity value measured will be low and the t_o correction large. Therefore, Lentz recommends that this time correction method be used for testing of dense samples only. D'Eustachio and Schreiner (1952) even discard the correction method and take just the straight line portion of the temperature versus ln t plot for analysis. They note that such a correction is not necessary except for more precise work. Hooper and Lepper (1950) argue that the thermal conductivity probe should be recognized as a primary standard test instrument itself and therefore no calibration against any other standard material should be required, although the authors also adopt the time correction method of analysis. De Vries and Peck (1958) agree that the probe method can be applied with confidence for measurements of thermal conductivity. It is also stated in the ASTM (1970) standard that the probe method is an absolute test for thermal conductivity determination directly. No calibration based on a specimen of known thermal conductivity is required. In case of a dispute, the Standard recommends that the thermal conductivity value established by the guarded hot plate test (ASTM, 1982) be treated as accurate. However, as noted earlier, the standard guarded hot plate apparatus is only good for testing dry and homogeneous materials.

Rather than using the time correction method mentioned above, Hooper and Chang (1953) have also attempted to use a position adjustment which alters the radial distance, r, of the thermocouple in the $r^2/4\alpha t$ term of equation 3.8. A graphical method has been designed to find the thermal conductivity of a material by successive approximation. The authors note that the r term is not constant for the same probe with different materials. This is the same case as the time correction, t_0. One can only treat the r term as an apparent radial distance of the thermocouple as opposed to an actual distance.

Although both the time and the position adjustment methods may yield better results than those derived from uncorrected time-temperature data, the results can only be taken as approximate. The application of the methods is limited by probe size and sample density as discussed previously. Furthermore, thermal contact resistance at the sample and probe interface, although generally small, may become significant for tests with high ambient temperature and/or large power input. Realizing the limitations of these empirical correction methods, Blackwell (1954) developed another solution to the governing partial differential equation (3.6) by using the actual boundary condition that the medium is bounded internally by a hollow probe of finite diameter. The assumptions of an infinite medium and an infinite extent of the probe along the longitudinal axis are still applicable in his analysis. Together with the assumption that the probe wall is made of perfectly conducting material, Blackwell found the following approximate solution for equation 3.6, for large experimental times:

$$T = A \ln t + B + \frac{1}{t} (C \ln t + D) \qquad 3.13$$

where: $A = q_i / 4\pi k$ (°C)

$B = A \left[\ln (4\alpha / r_0^2) - \gamma + 2k / r_0 H \right]$ (°C)

r_0 = External radius of the probe (m)

H = Heat transfer coefficient at the probe-sample interface, at $r = r_0$ (W/m^2 °C) (a measure of thermal contact resistance)

$T, t, q_i, k, \alpha, \gamma$ are as defined previously, and C,D are functions of the constants of the problem but are not required in the evaluation of k and α.

If the thermal conductivity test apparatus is appropriately designed such that the last term of equation 3.13 involving the coefficients C and D is negligible, Blackwell's solution can be simplified as follows:

$$T = A \ln t + B \qquad 3.14$$

It can be observed immediately that equation 3.14 reduces to the same form as equation 3.11 for two different time-temperature measurements. That means the thermal conductivity value of a material can be estimated directly from the slope (A) of the temperature versus ln t plot.

Blackwell (1954) has shown that results predicted by equation 3.13 compare reasonably well with numerical integration of the exact real integral solution. He suggests the use of a least-squares multiple linear regression analysis on the time-temperature record to evaluate the four coefficients A, B, C and D of equation 3.13. The method of analysis can be systematized by means of a computer program. Thermal conductivity of the test specimen is evaluated from the computer calculated coefficient A.

Since the assumptions of a perfect probe conductivity and of radial flow have been proven to be valid at least for large time measurements by Blackwell (1954, 1956), equation 3.13 appears to be the best representation of the transient state thermal conductivity probe test thus far. Jaeger (1956) also obtained the same equation (3.13) as Blackwell's, except that Blackwell also considered the 'small time' solution although it is of limited significance in the thermal conductivity probe test.

Noting that Blackwell (1954) used a probe with the heating element wound outside it and a temperature measuring device attached to its inner wall surface, which is not too common in practice, de Vries and Peck (1958) devised a new probe with the heater and thermocouple housed inside a Monel gauze. Paraffin wax was used as infilling material. Treating the probe conductivity as finite, the authors then found a new solution for equation 3.6. The solution is quite general and covers almost all the deficiencies of assumptions made by previous investigators in their attempts to simulate the line source conditions. However, in order to carry out the analysis, one has to assume or know the thermal properties of the probe heater. This renders a drawback to de Vries and Peck's method as such thermal properties are seldom known or given if the probe is purchased instead of being assembled by the investigator.

Recommended Method of Analysis

It should be noted that for a probe of infinite conductivity, Blackwell's (1954) solution for equation 3.6 is the same as that of de Vries and Peck (1958). If this assumption can be justified, it is more convenient to use Blackwell's solution because of its simplicity. No approximations of the thermal properties and density of the probe are required in solving equation 3.13.

Since the wall thickness of the probe is very small, it can reasonably be assumed that the temperatures are the same both at the inside and outside surfaces of the probe wall. In essence, thermal conductivity of the probe wall can be assumed to be infinite, and hence placing the heater inside or outside the wall should not result in too much a deviation from Blackwell's assumptions. In fact, Blackwell (1954) has looked into the condition of having a probe with finite conductivity. He points out the fact that the effect of finite probe conductivity on the 'large time' solution is so small that it can be neglected so far as the determination of thermal conductivity and diffusivity is concerned. The finite probe conductivity only plays a significant role in the 'small time' solution. De Vries and Peck (1958) also agree that, in most cases, application of the simple line source theory is permissible with probes made by other researchers. This is particularly true when thermal conductivity testing is performed on dense materials for large times and small power input. Woodside and Messmer (1961) point out the merit of having the thermocouple attached to the outside surface of the probe at mid-height that a smoother time-temperature record can be obtained.

Considering the pros and cons of the different methods of thermal conductivity analysis, the author finds Blackwell's (1954) method the most appropriate in simulating the test set-up used in this study and in giving a simple and systematic approach to the analysis of results. The cylindrical heat source theory is well suited for a more accurate determination of the thermal conductivity of a material. Blackwell's equation (3.13) can be applied to estimate the thermal conductivity value without the knowledge of the thermal properties and density of the probe, the thermal contact resistance or the radial distance of the temperature sensing device near the probe.

To help fulfilling the assumptions of the transient state thermal conductivity probe test, the following recommendations may be followed:

1. Design a probe such that the axial heat loss to the ends and the temperature gradient across the surface of the probe are minimized.
2. Use small power inputs to avoid high thermal gradients and thermal contact resistance around the probe.
3. Use samples with large enough diameters such that the heat reaching the sample boundary is a lot less than the heat being generated at the probe.
4. Use test periods that are short to better simulate the infinite medium but are long enough that Blackwell's 'large time' solution may be used.
5. Apply a confining pressure to the soil/rock sample equivalent to the *in situ* pressure. This procedure not only represents a better simulation of the *in situ* conditions but also reduces the contact resistance at the probe surface as the sample should have a tighter contact with the probe.

As discussed previously, if the last term of equation 3.13 involving the coefficients C and D is negligible, the equation reduces to the form of a linear temperature function with the independent variable being the natural logarithm of time (equation 3.14). The thermal conductivity value of a material can be found directly from the slope (A) of the linear relationship, and the temperature axis intercept (B) will yield the thermal diffusivity value provided that the heat transfer coefficient of the probe-sample interface (H) is known or assumed to be very large. If the above recommendations (design criteria to be stated in the following chapter) are followed, it can reasonably be assumed that the last term of equation 3.13 is negligible. Instead of a multiple linear regression, a simple least-squares linear regression analysis can be carried out on the time-temperature data, using equation 3.14, for the evaluation of the thermal conductivity and diffusivity of a material.

From preliminary tests made by the thermal test cell (Figure 3.11) used in this study, it has been found that the temperature versus ln t plots are quite linear, indicating that the contributions of the C and D coefficients are very small. It has also been noted that the multiple linear regression analysis is quite sensitive to the scatter of data points and to the number of data entries. On the other hand, results obtained from the simple linear regression analysis using the simplified Blackwell's equation (3.14) are quite consistent. Therefore, it is proposed that the simplified version of Blackwell's theory be used in the current study. For a brief review of the least-squares regression theory, one may refer to Ang and Tang (1975).

Since the basic assumption used in deriving the line heat source theory (equation 3.8) requires that the initial temperature throughout the medium be zero, the initial ambient temperature should be treated as a reference temperature. All measured temperatures should be subtracted by this ambient temperature to obtain a temperature rise record for subsequent graph plotting and calculations.

3.3.2 Thermal Diffusivity

3.3.2.1 General Theory

Contrary to the transient state thermal conductivity testing in which a constant line source is generated along the longitudinal axis, a thermal diffusivity test generally involves the heating or cooling of the cylindrical sample surface. One method of thermal diffusivity testing is immersing a sample with uniform initial temperature into a bath of constant temperature fluid and monitoring the time-temperature response of the sample. However, in the development of a general theory, an infinite cylinder is assumed so that radial heat flow in the uniform homogeneous medium is one-dimensional. As in the case of a thermal conductivity test, the effects of radiation and convection are assumed to be either negligible or incorporated into the result.

The governing differential equation is still equation 3.6 and the new boundary conditions are stated as follows:

1. Zero initial temperature throughout the medium, except at the surface.
2. Surface temperature is a function of time, $\phi(t)$.

The solution can be found in Carslaw and Jaeger (1959) and is stated as follows:

$$T = \frac{2\alpha}{R_0} \sum_{n=1}^{\infty} e^{-\alpha\delta_n^2 t} \frac{\delta_n J_0(r\delta_n)}{J_1(R_0\delta_n)} \int_0^t e^{\alpha\delta_n^2\lambda} \phi(\lambda)\, d\lambda \tag{3.15}$$

where: T = Temperature as a function of r and t (°C)

α = Thermal diffusivity of the medium (m^2/s)

R_0 = External radius of sample (m)

δ_n = ($n=1,2,3,\ldots$) Positive roots of the function, $J_0(R_0\delta)=0$ (dimensionless)

t = Time (s)

r = Radial distance from centre of cylinder (m)

$J_0(x), J_1(x)$ = Bessel function of order 0 and 1 respectively

$\phi(t)$ = Surface temperature of sample as a function of time (°C)

3.3.2.2 Methods of Analysis

Previous Work

If the temperature function at the surface of the cylindrical sample is assumed to be constant (i.e. $\phi(t) = V = \text{constant}$), then equation 3.15 becomes:

$$T = V - \frac{2V}{R_0} \sum_{n=1}^{\infty} e^{-\alpha \delta_n^2 t} \frac{J_0(r\delta_n)}{\delta_n J_1(R_0\delta_n)} \qquad 3.16$$

Let $\beta_n = R_0\delta_n$ 3.17

and $\tau = \alpha t/R_0^2$ 3.18

equation 3.16 becomes:

$$\frac{T}{V} = 1 - 2 \sum_{n=1}^{\infty} e^{-\beta_n^2 \tau} \frac{J_0(r\beta_n/R_0)}{\beta_n J_1(\beta_n)} \qquad 3.19$$

where $+\beta_n$, $n=1,2,3,\ldots$, are the roots of $J_0(\beta)=0$, and r is the radial distance of the temperature measurement point from the central axis of the cylinder. If the temperature sensing device is placed right along this central axis, r is zero and the Bessel function of order zero term becomes unity.

The only independent variable in equation 3.19 is τ. By assuming values for τ, the ratio of the measured temperature at time, 2t, to the temperature at time, t, can be evaluated and a graph of $T(2t)/T(t)$ versus τ may then be plotted (Figure 3.14). Jaeger (1959) proposed this graphical method to evaluate the thermal diffusivity of rock. Enniss *et al* (1978) used the same method for their diffusivity analysis. For details of the method, refer to Jaeger (1959).

Jaeger admits the inherent disadvantage of this method is that it is difficult to maintain a constant surface temperature. However, for diffusivity testing of poor conductors, the disadvantage is not too prominent. Jaeger also suggests that the method is particularly well suited to diffusivity testing of water saturated rocks.

Jaeger's method of analysis requires that the test specimen, which is initially at a constant temperature, V_0, be immersed (at $t=0$) in a medium of a fixed temperature, V_1. In order to satisfy the boundary condition that the cylinder has zero initial temperature, all temperature measurements will have to be reduced by V_0. Thus the constant surface temperature term, V, is equal to $V_1 - V_0$ and all other temperature, T, are equal to T(measured) - V_0.

Enniss *et al* (1978) used Jaeger's method for their diffusivity analysis for rocks. However, instead of immersing the sample in a medium of fixed temperature, the authors achieved the required surface temperature by heating the surface of the specimen with an external heating coil around the base of the sample. Although it was not stated in their paper, it is suspected that there would be a time lag before the prescribed surface temperature was reached. Some heat would have migrated into the cylinder before the surface temperature actually became constant. Therefore, it would be prudent to account for this time lag, though small in some cases, and treat the surface temperature as a function of time instead of being a constant.

Theory Used in Current Research

As discussed in the previous section, it would be appropriate to establish a functional relationship between surface temperature and time when analyzing data from a transient state diffusivity test that employs the same experimental set-up as that of Enniss *et al* (1978). Equation 3.15 should then be used to evaluate thermal diffusivity of the test specimen.

It must be noted that when $r = R_0$, equation 3.15 gives $T = 0$ for all values of t, which is certainly contrary to the boundary condition. Therefore, the equation is valid only for $r < R_0$. If it is required that equation 3.15 be valid for R_0 also, some mathematical manipulations involving Bessel functions are warranted. For instance, if the surface temperature is a linear function of time such as $\phi(t) = bt$, where b is a constant, Carslaw and Jaeger (1959) has a solution for equation 3.6 as follows:

$$T = b\left(t - \frac{R_0^2 - r^2}{4\alpha}\right) + \frac{2b}{R_0\alpha}\sum_{n=1}^{\infty} e^{-\alpha\delta_n^2 t}\frac{J_0(r\delta_n)}{\delta_n^2 J_1(R_0\delta_n)} \qquad 3.20$$

Churchill (1941) and McLachlan (1934) may be consulted for the necessary formulae required to achieve the above equation. The equation (3.20) is also valid for $r = R_0$ as it reduces to $T = bt = \phi(t)$ at that point.

In order to use Jaeger's method in evaluating the thermal diffusivity value of a material, equation 3.20 may be modified as follows:

1. Multiply α to both sides of equation 3.20 gives:

$$T\alpha = b\left(\alpha t - \frac{R_0^2 - r^2}{4}\right) + \frac{2b}{R_0}\sum_{n=1}^{\infty} e^{-\alpha\delta_n^2 t}\frac{J_0(r\delta_n)}{\delta_n^2 J_1(R_0\delta_n)} \qquad 3.21$$

2. Substituting equations 3.17 and 3.18 gives:

$$T\alpha = b\left(R_0^2\tau - \frac{R_0^2 - r^2}{4}\right) + 2bR_0 \sum_{n=1}^{\infty} e^{-\beta_n^2\tau} \frac{J_0(r\beta_n/R_0)}{\beta_n^2 J_1(\beta_n)} \tag{3.22}$$

The only unknown on the right hand side of equation 3.22 is now τ. When $T(2t)$ is divided by $T(t)$ as for $T(2t)/T(t)$, the α term drops off. Therefore, Jaeger's method is applicable if the surface temperature of the sample is a linear function of time (i.e. $\phi(t) = bt$).

However, the rate of temperature rise at the sample surface is not generally linear. In order to cover a wider range of variable temperature functions, the term $\phi(t)$ in equation 3.15 will have to be general. It is thus proposed that a power series expansion of the temperature function $\phi(t)$ be employed.

Analysis has shown that a seventh order polynomial, such as

$\phi(t) = A_0 + A_1 t + A_2 t^2 + A_3 t^3 + A_4 t^4 + A_5 t^5 + A_6 t^6 + A_7 t^7$,

is sufficient for this purpose. The major reason for choosing a polynomial instead of any other function to represent $\phi(t)$ is that it is easier to integrate with the $\exp(-\alpha\delta_n^2 t)$ term in equation 3.15.

With $\phi(t)$ being a seventh order polynomial, equation 3.15 is expanded and the following equation results:

$$T = 2 \sum_{n=1}^{\infty} \frac{J_0(r\beta_n/R_0)}{\beta_n J_1(\beta_n)} \left[\left(A_0 - \frac{W_1}{a_n}\right)\left(1 - e^{-a_n t}\right) + W_1 t \right.$$

$$\left. + W_2 t^2 + W_3 t^3 + W_4 t^4 + W_5 t^5 + W_6 t^6 + A_7 t^7 \right] \quad 3.23$$

where: $a_n = \alpha \delta_n^2$, $\beta_n = R_0 \delta_n$

$$W_1 = A_1 - \frac{2A_2}{a_n} + \frac{6A_3}{a_n^2} - \frac{24A_4}{a_n^3} + \frac{120A_5}{a_n^4} - \frac{720A_6}{a_n^5} + \frac{5040A_7}{a_n^6}$$

$$W_2 = A_2 - \frac{3A_3}{a_n} + \frac{12A_4}{a_n^2} - \frac{60A_5}{a_n^3} + \frac{360A_6}{a_n^4} - \frac{2520A_7}{a_n^5}$$

$$W_3 = A_3 - \frac{4A_4}{a_n} + \frac{20A_5}{a_n^2} - \frac{120A_6}{a_n^3} + \frac{840A_7}{a_n^4}$$

$$W_4 = A_4 - \frac{5A_5}{a_n} + \frac{30A_6}{a_n^2} - \frac{210A_7}{a_n^3}$$

$$W_5 = A_5 - \frac{6A_6}{a_n} + \frac{42A_7}{a_n^2}$$

$$W_6 = A_6 - \frac{7A_7}{a_n}$$

The integration procedure is quite straight forward and is included in Appendix B.

It should be noted that this equation (3.23) is not applicable at $r = R_0$ because the J_0 function will approach zero. An attempt was made to simplify this equation to a form similar to equation 3.20, but the effort was proven futile due to the complex nature of the equation (3.23). Since only the internal sample temperature, which is far from $r = R_0$, is of interest, equation 3.23 is adequate for thermal diffusivity determination.

Proposed Method of Analysis

It can be seen that using the previous substitution, i.e. equation 3.18, will not result in a temperature function with a single independent variable, τ, alone. The different powers of $a_n = \alpha\delta_n^2$ do not allow the representation of α and t by a single variable. Hence, Jaeger's method cannot be employed.

The following method of analysis is proposed:

1. Use a least-squares multiple linear regression method to solve for the eight coefficients in the power series representation of the external surface temperature record.
2. With other variables in equation 3.23 known, temperature distribution in the medium is only dependent on a_n, or specifically α. An iterative procedure, namely *regula-falsi* method of finding roots of an equation, may be employed to find the diffusivity value for each time-temperature

data pair measured by the internal thermocouple. An average diffusivity value may be obtained from the calculated values at different time intervals.

Abramowitz and Stegun (1972) may be consulted for values of the Bessel functions. Computer programs for evaluating β_n's, Bessel functions and for performing multiple linear regression as well as diffusivity analysis have been written for the current study.

Probable Errors and Justifications

Since the entire sample tube is wrapped around by the silicon rubber heating jacket (Figure 3.11), heat tends to flow inwards one-dimensionally. Radial flow condition is warranted at least at mid-height of the sample where both internal and external temperature responses are monitored. If a radial heat flow condition is achieved, there is little to no thermal gradient along the axis of the cylinder. Therefore, loss of heat axially along the central probe and the thermocouple may be assumed to be negligible. With the two ends of the sample insulated by ceramic caps of low thermal conductivity, end effects should also be very small to affect the temperature measurements at mid-height of the sample.

Preliminary tests have shown that the thermal diffusivity values obtained from different time-temperature rise data pairs in a single test are quite consistent. This indicates that one-dimensional radial heat flow occurs at least along the cross-sectional plane at mid-height of the sample such that the diffusivity theory is applicable.

Although the finite configuration of the cylinder departs from the assumption of an infinite cylinder, the deviation of the diffusivity result is less than 10% (for $\tau < 0.2$) according to Jaeger (1959) (Figure 3.14). The finite cylinder used in Jaeger's calculation has a length to diameter (L/d_o) ratio of only one. With a L/d_o ratio of two for the sample dimensions used in this study, the error should be considerably less than 10%.

Since both the internal and external thermocouples are in intimate contact with the dense sample, thermal contact resistance is assumed to be negligible and is ignored in the thermal diffusivity analysis. Although the contact resistance may become large at elevated temperatures, its effect on the accuracy of the thermal diffusivity test is not too significant. Unlike the case of the thermal conductivity test where the entire probe surface area is subjected to the contact resistance effect, the contact area now in question only involves the small thermocouple tip which is well embedded in the sample.

Thermal Diffusivity from Thermal Conductivity Probe Test

Several investigators, namely Blackwell (1954), de Vries and Peck (1958), Woodside (1958), Jaeger (1959), Nix *et al* (1967, 1968), and van Haneghem and Boshoven (1979) have suggested that thermal diffusivity of a material can be estimated from a thermal conductivity probe test alone, provided that the conductivity value has already been established.

Assuming that thermal contact resistance across the external surface of the probe to be negligible (i.e. $H \rightarrow \infty$) or if it is known, thermal diffusivity of the test specimen can be calculated from the coefficient B as given in Blackwell's (1954) equation (3.13). For better approximation, Blackwell (1954) suggests a method of delineating the value of heat transfer coefficient, H, from the initial portion of the time-temperature record ('short time' solution). However, a knowledge of the thermal properties of the probe is required for the analysis. This suffers the same drawback as de Vries and Peck's (1958) method of analysis. If the test specimen is a dense material in intimate contact with the probe, it is reasonable to assume near perfect contact between the probe and the sample and thus dropping the $2k/r_0H$ term in the expression for B.

Woodside (1958) estimates thermal diffusivity of a sample by assuming r (in the $r^2/4\alpha t$ term of equation 3.8) to be one half the diameter of the probe (i.e. R_0). His experimental results from back calculations agree reasonably well with published data. Jaeger (1959) uses the complete time-temperature curve (equation 3.8) for the determination of both thermal conductivity and diffusivity. Nix *et al* (1967, 1968) have written computer programs that automatically handle the successive approximation of diffusivity from each time-temperature record. However, all of these authors have neglected the effect of thermal contact resistance on the measured thermal conductivity and subsequently thermal diffusivity values. Therefore, their methods may not be too reliable in all cases.

With the reasonable assumption that the probe is highly conductive, Blackwell's (1954) equation (3.13) or its simplified version (equation 3.14) should be employed to establish a good thermal conductivity approximation for the test specimen. Thermal contact resistance may then be used (if known) or assumed to be negligible (if small) for the calculation of thermal diffusivity using the coefficient B. Thermal contact resistance may be assumed to be small if the test specimen is dense, fully saturated, and tested with a confining pressure and a low power input. Since thermal contact resistance increases with temperature, its effect should be considered in thermal conductivity testing at elevated temperatures. If the thermal properties of the probe mass are given and the thermocouple is placed along the central axis of the probe, it is recommended that de Vries and Peck's (1958) method of analysis be followed, though Blackwell's (1954) method may also give a good approximation.

In using the simplified Blackwell's equation (3.14) the thermal diffusivity value is estimated from the temperature axis intercept (B). The accuracy of this approximation is not too high since a small deviation of the slope (A) of the linear temperature-ln t relationship will reflect a large error in the calculation of thermal diffusivity based on the logarithmic time scale. Furthermore, the evaluation of diffusivity is highly sensitive to the apparent radial distance of the internal thermocouple from the centre of the sample. As noted by Hooper and Chang (1953), this apparent radial distance is not constant for the same probe with different materials (Section 3.3.1.3). Therefore, the thermal diffusivity value obtained from a thermal conductivity probe test may not be accurate except for the order of magnitude.

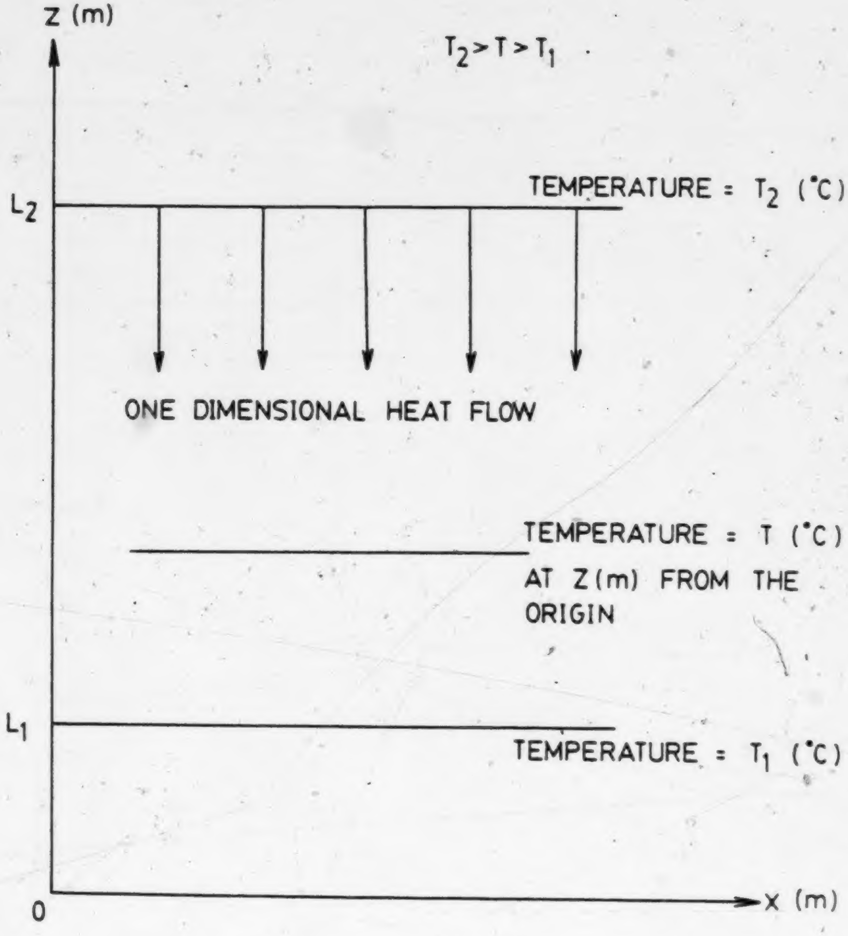


Figure 3.1 Steady State One-dimensional Linear Heat Conduction in a Uniform Homogeneous Medium

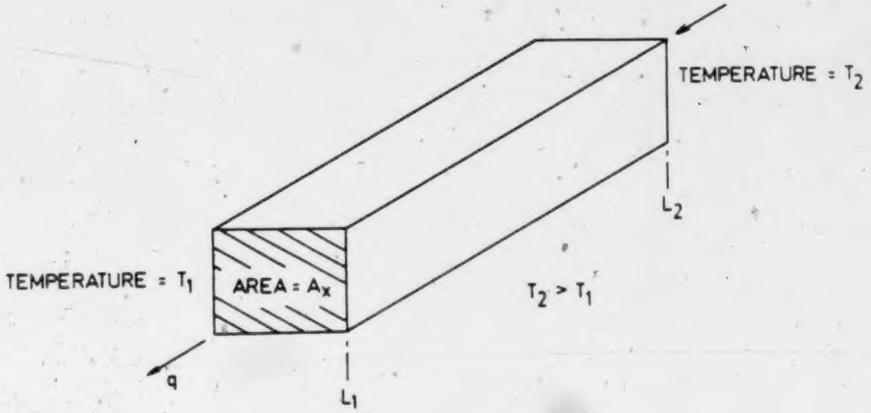


Figure 3.2 Heat Flow through a Prismatic Element

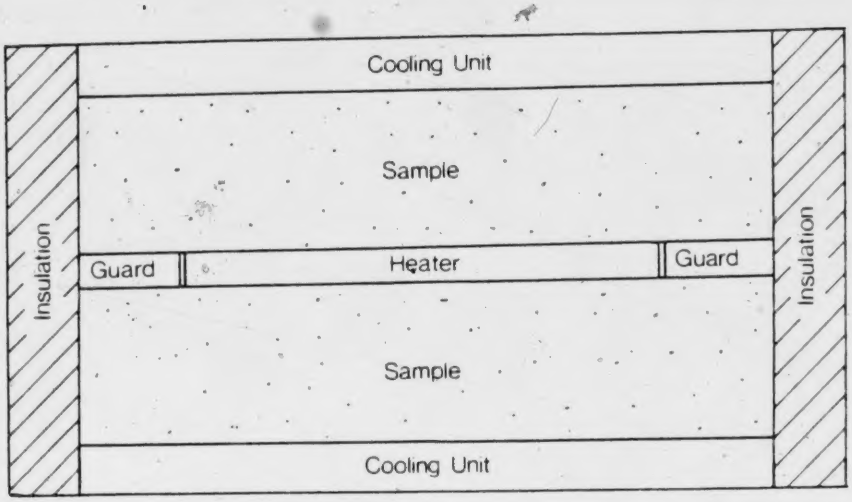


Figure 3.3 General Features of the Guarded Hot Plate Apparatus (ASTM, 1982)

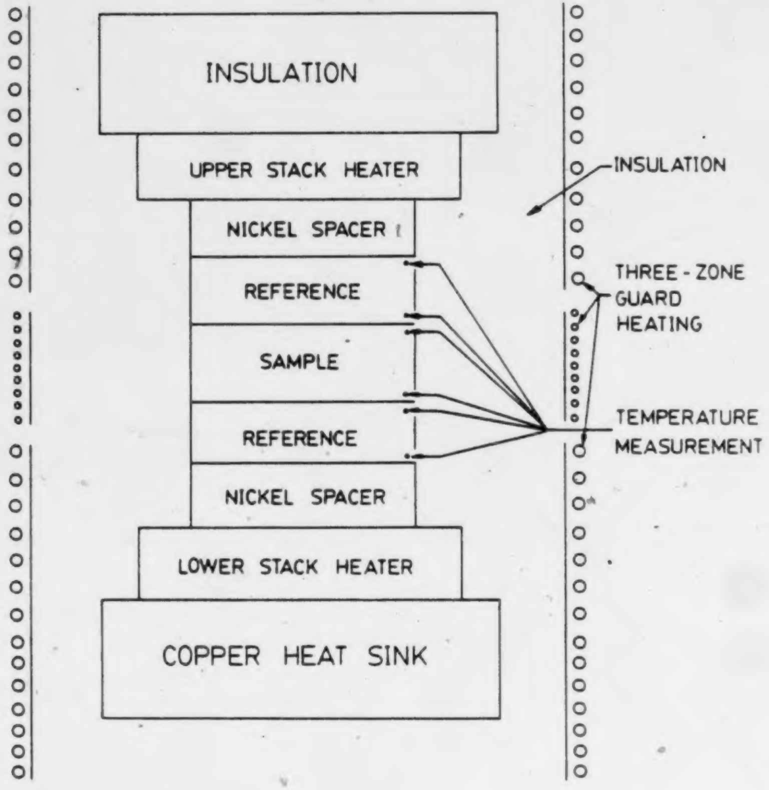


Figure 3.4 Stack Assembly for Thermal Comparator Technique (after DuBow, 1977)

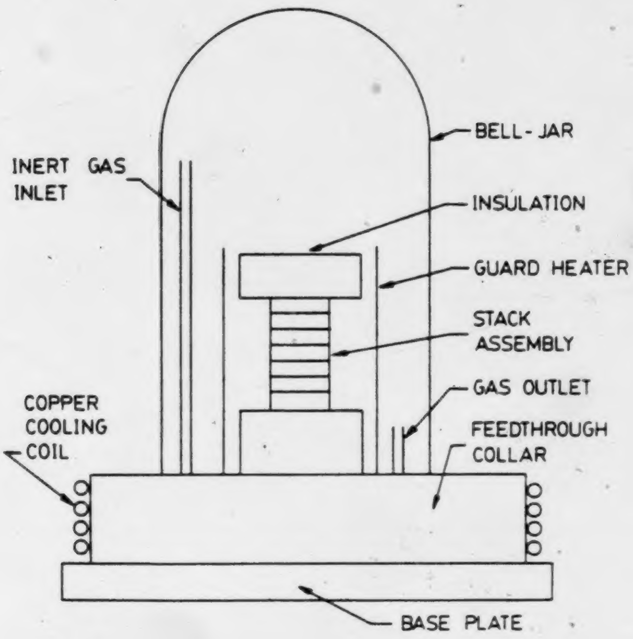


Figure 3.5 Schematic Diagram of Experimental Set-up for Thermal Comparator (after DuBow, 1977)

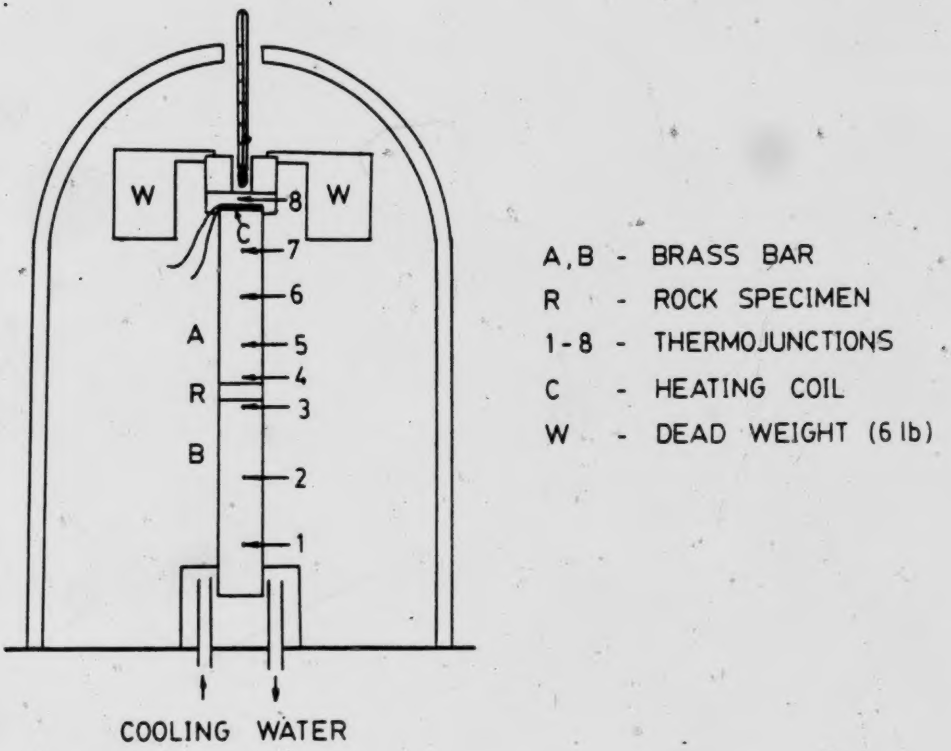


Figure 3.6 Divided Bar Apparatus (after Benfield, 1939)

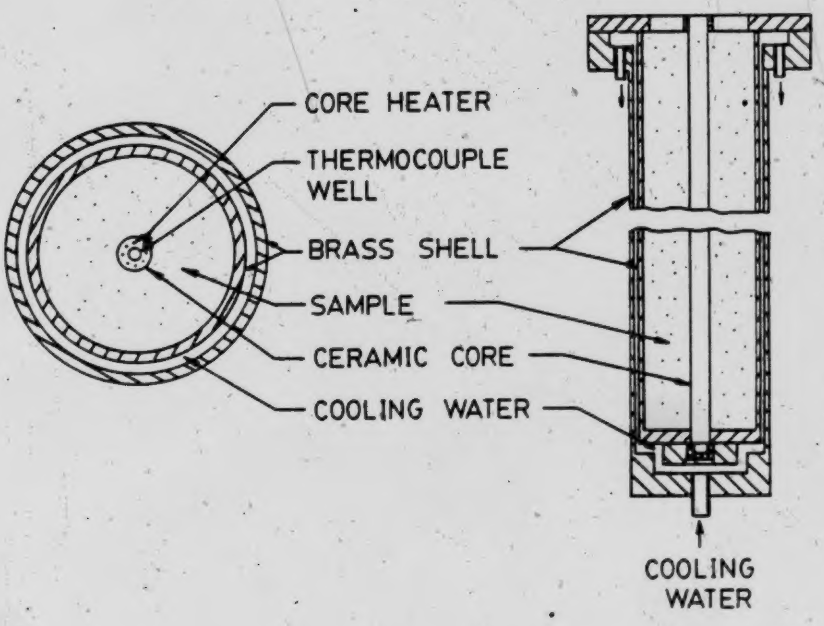


Figure 3.7 Steady State Coaxial Thermal Testing Apparatus (after Flynn and Watson, 1969)

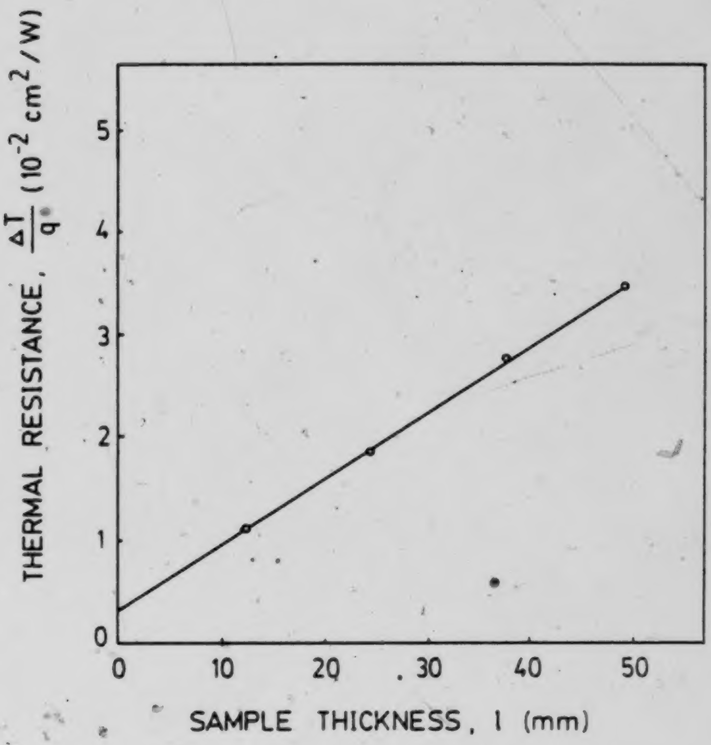


Figure 3.8 Thermal Resistance versus Sample Thickness (after Cervenan, Vermeulen and Chute, 1981)

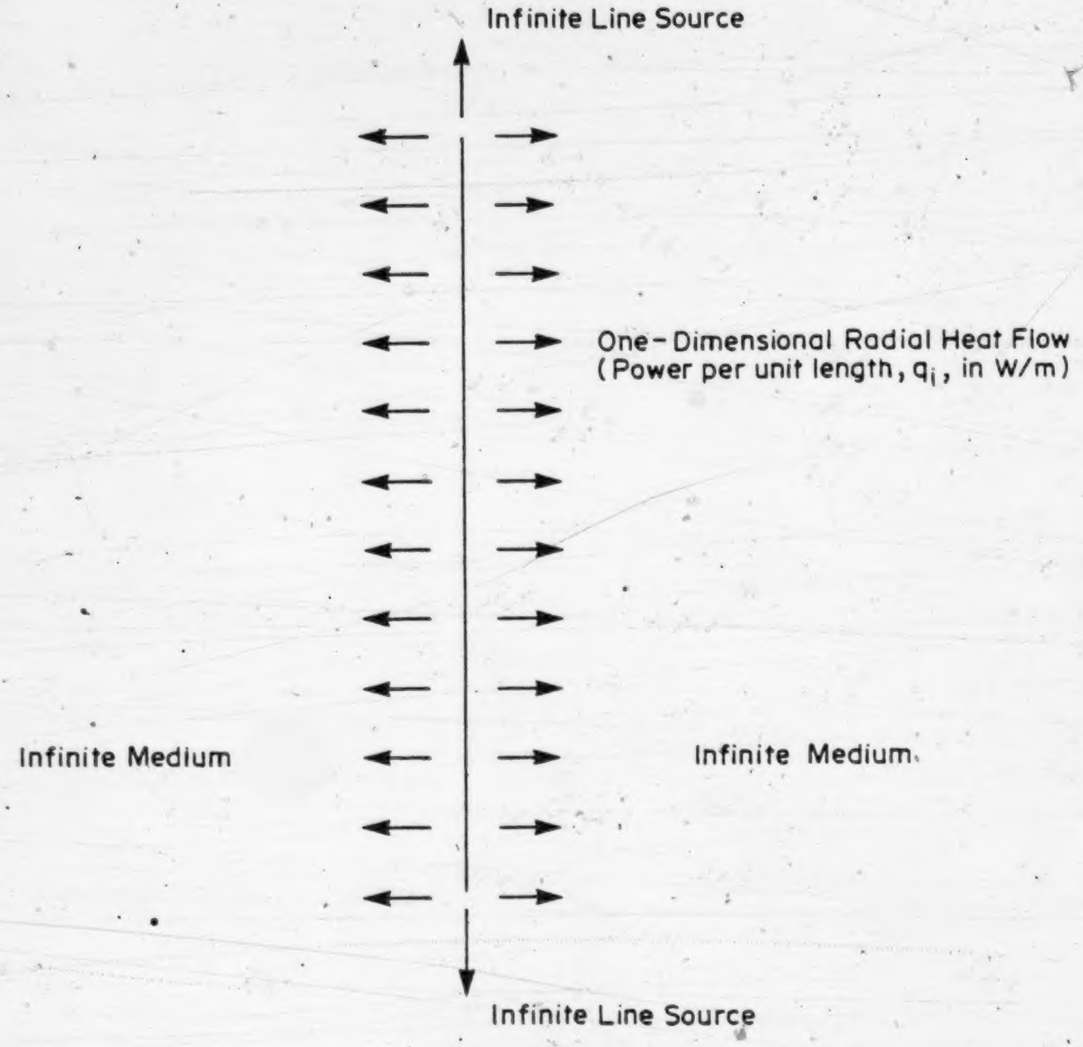

Infinite Line Source
One-Dimensional Radial Heat Flow
(Power per unit length, q_l, in W/m)
Infinite Medium
Infinite Medium
Infinite Line Source

Figure 3.9 Transient State One-dimensional Radial Heat Conduction in a Uniform Homogeneous Medium

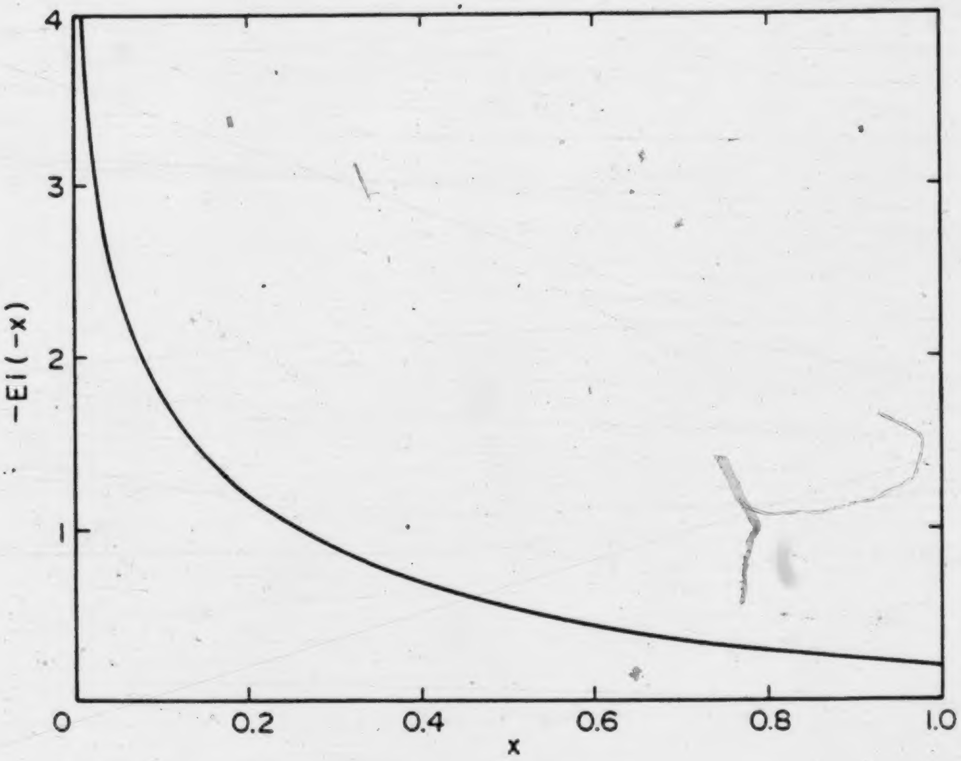


Figure 3.10 The Exponential Integral, -Ei(-x)

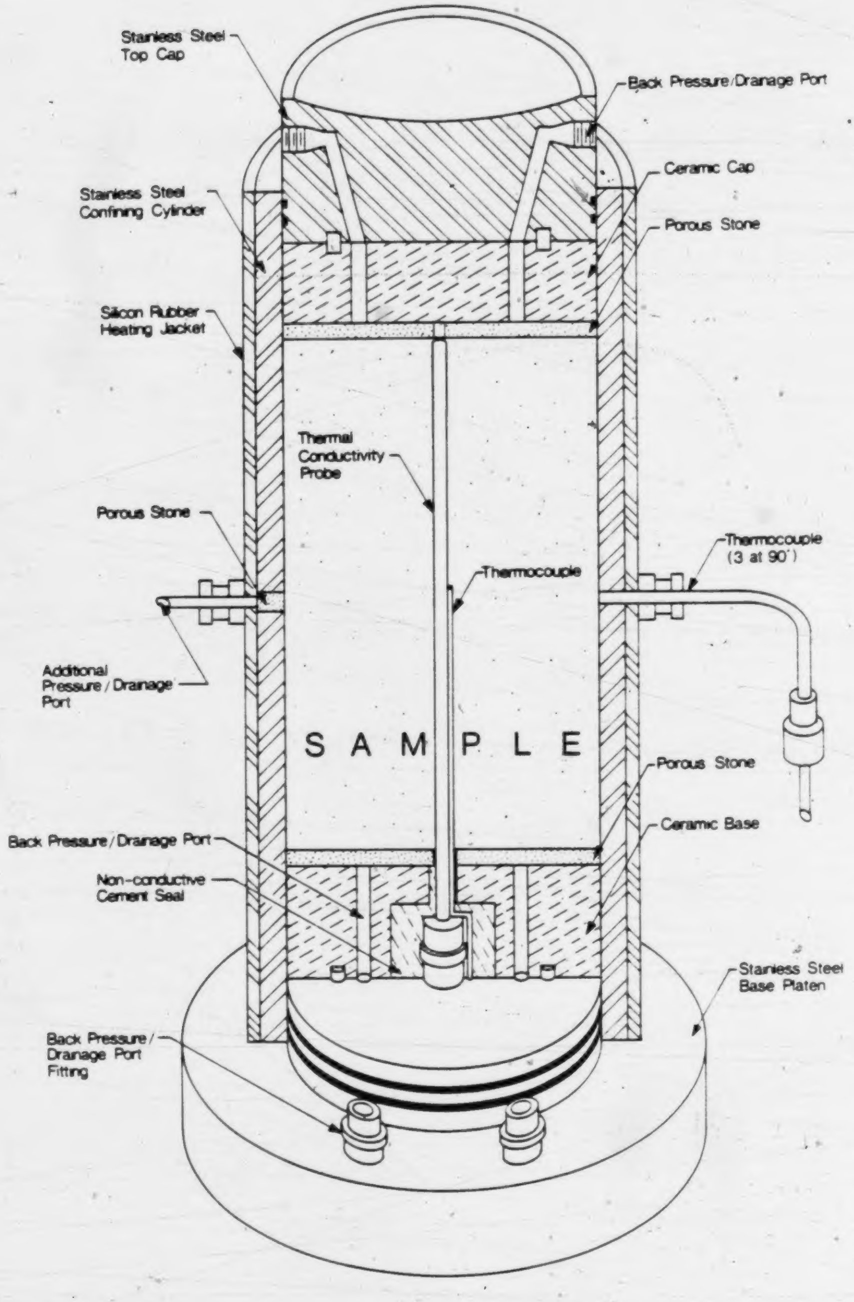

Stainless Steel Top Cap
Back Pressure/Drainage Port
Ceramic Cap
Stainless Steel Confining Cylinder
Porous Stone
Silicon Rubber Heating Jacket
Thermal Conductivity Probe
Porous Stone
Thermocouple (3 at 90°)
Thermocouple
Additional Pressure / Drainage Port
SAMPLE
Porous Stone
Ceramic Base
Back Pressure / Drainage Port
Non-conductive Cement Seal
Stainless Steel Base Platen
Back Pressure / Drainage Port Fitting

Figure 3.11 Transient State Thermal Test Cell

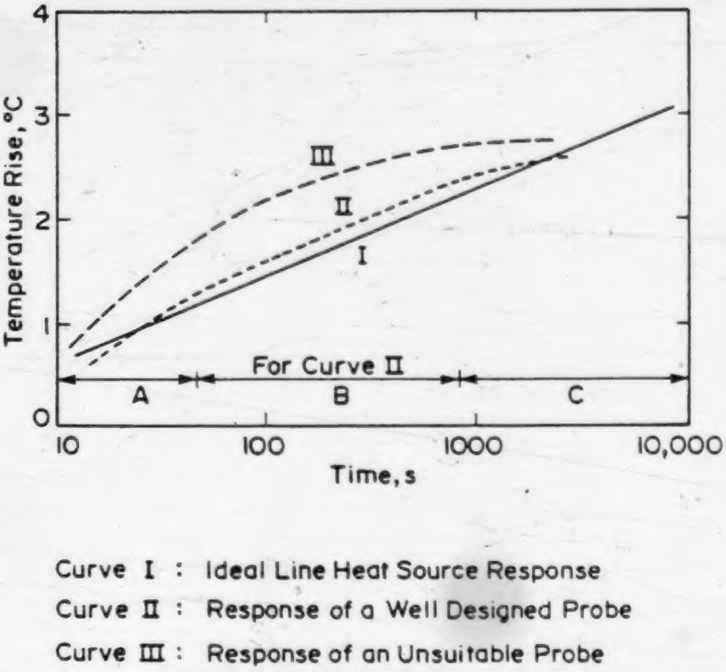


Figure 3.12 Typical Probe Temperature-Time Profiles (after Wechsler, 1966)

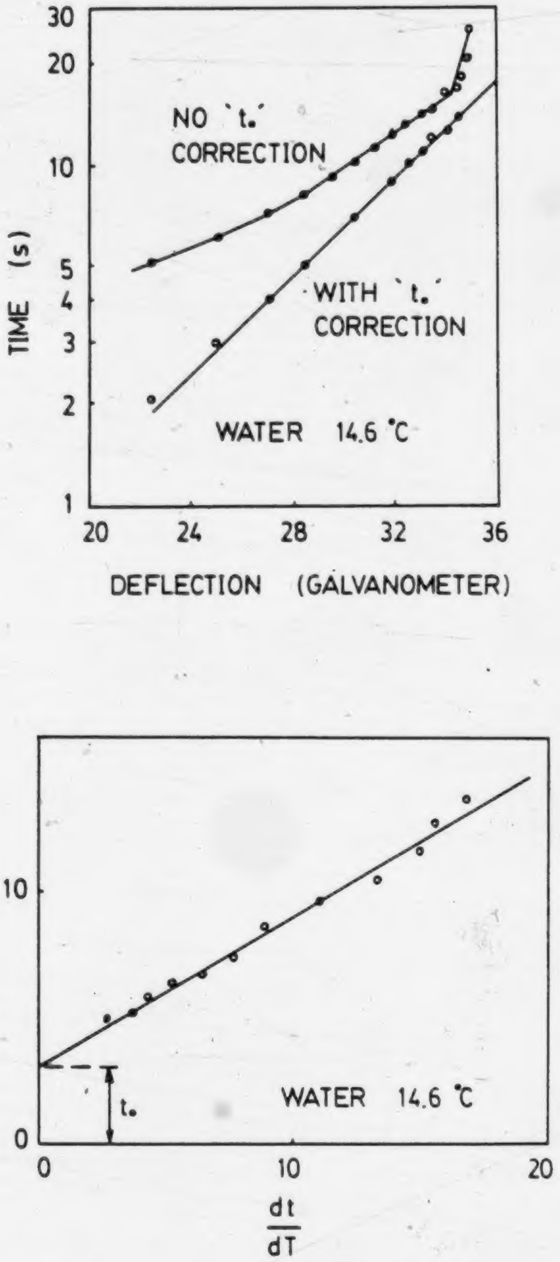


Figure 3.13 Determination of "to" Correction (after van der Held and van Drunen, 1949)

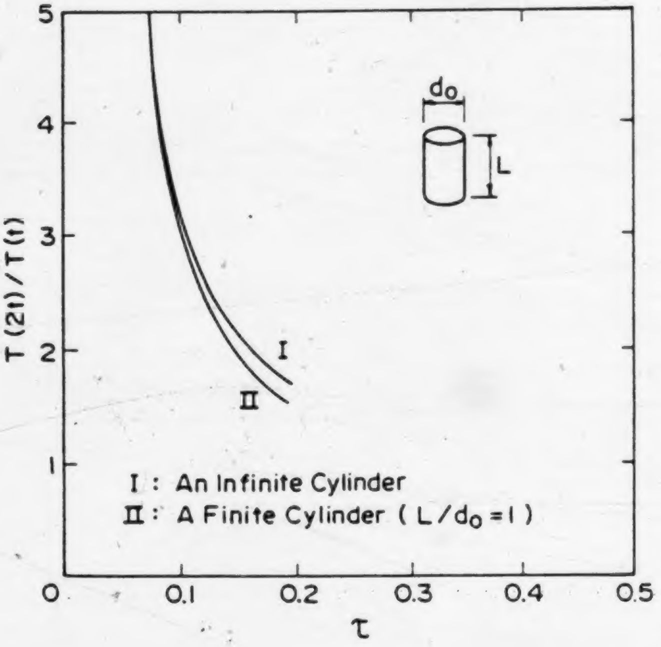


Figure 3.14 Values of T(2t)/T(t) at the Centre of a Cylinder as a Function of τ (after Jaeger, 1959)

4. LABORATORY TESTING

4.1 Introduction

The laboratory apparatus required for thermal conductivity and thermal diffusivity determination include the thermal test cell, the high pressure and temperature triaxial compression cell, a dc power supply unit, a pore pressure injection system, a hot water generator, temperature controllers and a data acquisition system. Each of these pieces of equipment will be described briefly in this chapter. Procedures for preparing, mounting, saturating and air or hot water flushing a test specimen are described. Recommended methods of thermal testing and the testing program are also outlined. To characterize the physical properties of the test samples, index tests which consist of the determination of bulk density, grain size distribution as well as bitumen and water contents were carried out.

The thermal test cell, when housed in the triaxial test system used by Agar (1984), can be operated at temperatures ranging from room temperature to 200 °C (390 °F) and at pore fluid pressures up to 10 MPa (1500 psi). The thermal testing apparatus is capable of measuring both thermal conductivity and diffusivity of a material at the specified range of operational temperatures and pressures.

4.2 Laboratory Apparatus

4.2.1 Steady State Hot Plate Apparatus

Prior to the thermal conductivity testing using the transient state thermal test cell, the steady state hot plate apparatus (Figure 4.1) devised by Cervenan, Vermeulen and Chute (1981) was used to determine the thermal conductivity values of dry and water saturated quartz sand. The results obtained will be used for later discussions. For details of the design and specifications of the hot plate apparatus, one may refer to Vermeulen *et al* (1982).

4.2.2 Transient State Thermal Test Cell

4.2.2.1 General Features and Design Criteria

Figure 4.2 displays the main features of the high pressure and temperature triaxial compression test cell which houses the thermal test cell. Details of the specifications and dimensions of each component of the thermal test cell are included in Appendix C. Agar's (1984) thesis may be consulted for details of the triaxial test assembly. The entire test assembly is connected with the necessary peripherial systems for power supply, confining pressure and back pore pressure generation, temperature control, air or hot water flushing as well as data acquisition.

Details of the transient state thermal test cell are shown in Figure 3.11. The internal thermocouple is silver-soldered to the side of the thermal conductivity probe which is fastened to the stainless steel base platen by a fitting along the central axis of the apparatus. The stainless steel confining cylinder provides lateral confinement for the test specimen. The outer silicon rubber heating jacket around the confining cylinder permits fast and uniform heating of the sample surface. Three thermocouples are installed around the circumference of the sample surface at mid-height of the sample to monitor surface temperature. The ceramic top cap and base block insulate the specimen from axial heat transmission. A non-conductive cement is used to seal the cavity formed around the fitting at the cermaic base. Complete sealing of the sample from the external ambience is achieved by the installation of two rubber 'O'-rings near the base of the stainless steel top cap and two at the base platen.

To allow for the application of back pore fluid pressure and drainage through the specimen, five drainage ports are introduced into the test cell. A drainage path is formed from the bottom porous stone to the exterior of the base platen by the two ports located at the bottom of the assembly. The other two ports at the top of the apparatus permit passage of fluid from the upper porous stone to the exterior of the stainless steel top cap. An additional pressure/drainage port is provided at mid-height of the confining cylinder. This port may be used as a measurement point for an average pore fluid pressure when a pressure transducer is connected or may be utilized as an extra pressure application or drainage port when needed. For the current study, back pore fluid pressure is introduced via one of the lower drainage ports and fluids are allowed to drain out of the system from the top drainage ports.

As stated in the previous chapter, the proper selection of the probe and sample dimensions is very important if the transient state heat conduction theory is to be simulated to the best approximation. It is therefore worthwhile to discuss the criteria for the selection of the dimensions as follows:

Heated length to diameter ratio (L/d_0) *of the probe*:

To minimize the axial heat flow error in the thermal conductivity probe test, Blackwell (1956) proposed the following criterion:

$$\Delta R(\max) = \exp(-0.01(L/d_0)^2)(5.64(d_0/L) + 0.00680(L/d_0)\psi(\xi-\eta)) \qquad 4.1$$

where: $\Delta R(\max)$ = Maximum axial flow error (dimensionless)

L/d_0 = Heated length to diameter ratio of the probe (dimensionless)

ψ = $2d/r_0$ (dimensionless)

d = Wall thickness of the probe (mm)

r_0= External radius of the probe (mm)

ξ = k_1/k (dimensionless)

k_1= Thermal conductivity of the probe wall (W/m °C)

k = Thermal conductivity of the sample (W/m °C)

η = $\rho_1 c_1/\rho c$ (dimensionless)

ρ, ρ_1= Density of the sample and the probe wall respectively (g/cm^3)

c, c_1= Specific heat of the sample and the probe wall respectively (cal/g °C)

Given the probe dimensions and the probe characteristics (Wechsler, 1966):

L = 5.75 in (146.1 mm)

d_0= 0.125 in (3.2 mm) or r_0= 0.0625 in (1.6 mm)

d = 0.01 in (0.25 mm)

k_1= 16.24 W/m °C

ρ_1= 7.86 g/cm^3

c_1= 0.11 cal/g °C

and the sample parameters:

SAMPLE	k(W/m °C)	ρ(g/cm^3)	c(cal/g °C)
Dry sand	0.44	1.79	0.20
Sat. sand	3.47	2.10	0.32
Oil sand	1.56	2.13	0.24

where k and ρ of the sand were measured in preliminary tests and c of the sand was obtained from Wechsler (1966), and the parameters for oil sand were obtained from Cervenan, Vermeulen and Chute (1981), the axial heat flow error is estimated and tabulated below:

SAMPLE	$\Delta R(\max)$
Dry sand	2.4×10^{-09}
Sat. sand	3.0×10^{-10}
Oil sand	6.4×10^{-10}

The axial heat flow error is shown to be very small for the thermal conductivity probe test apparatus. In fact, Blackwell (1956) has shown that for a hollow brass probe (with thermal conductivity about seven times that of stainless steel), the maximum error is slightly under 1.0×10^{-2} if the L/d_0 ratio is 25. The probe used in this study (with $L/d_0 = 46$) certainly meets the requirement.

To justify the radial heat flow assumption, Blackwell (1954) proposed the following design criterion for the length of the probe:

$$L > \left(4\alpha t \,/\, 0.0632 \right)^{0.5} \qquad 4.2$$

where: L = Heated length of the probe (m)

α = Expected upper limit of the thermal diffusivity of the sample (m^2/s)

t = Largest test time expected (s)

For $t = 200$ s and $\alpha = 1.5\times10^{-6}$ m^2/s, estimated from preliminary tests, L has to be greater than 0.1378 m. The length of the probe, 0.1461 m, used in this study satisfies this radial flow criterion.

First valid point of thermal conductivity calculation from the time-temperature record:

As discussed previously, there exists an initial time lag which causes a curvature at the beginning of the temperature versus ln t plot for a typical thermal conductivity probe test. Since only the linear portion of the curve is valid for thermal conductivity evaluation, many researchers suggest that the probe radius and the test time be designed or adjusted such that:

$$r_o^2 / 4\alpha t \ll 1 \qquad 4.3$$

where: r_o = External radius of the probe (m)
α = Thermal diffusivity of the sample (m^2/s)
t = Time from the start of the test (s)

Knowing that $r_o = 1.59\times10^{-3}$ m and assuming that $r_o^2/4\alpha t \leq 0.0256$ (as suggested by Nix *et al* (1967) for a linear approximation of better than 1 % accuracy), the first valid measuring points for different thermal diffusivity values are estimated as follows:

THERMAL DIFFUSIVITY (m^2/s)	1st VALID TIME (s)
1.0×10^{-7}	246
2.5×10^{-7}	98
5.0×10^{-7}	49
7.5×10^{-7}	32
1.0×10^{-6}	25
1.5×10^{-6}	16

The valid times given above should be used as guidelines only. Actually, as long as a point of measurement falls within the linear portion of the temperature-ln t plot of a thermal conductivity test, the point is acceptable to be used in the evaluation of thermal conductivity.

Sample dimensions

The length of the sample is governed by the axial heat loss and radial flow criteria. Since the minimum length of the probe in the sample is 5.96 in (151.5 mm), the sample length must be a minimum of about 6.0 in (152.4 mm).

To minimize the amount of heat passing through the external sample boundary as compared to the heat generated by the heat source, de Vries and Peck (1958) proposed the following criterion for the sample radius:

$$\exp(- R_0^2 / 4\alpha t) << 1 \qquad 4.4$$

where: R_0 = External radius of the sample (m)

α = Thermal diffusivity of the sample (m^2/s)

t = Time for the heat front to reach the external sample boundary (s)

Wechsler (1966) suggests that:

$$\exp(- R_0^2 / 4\alpha t) = 0.02 \qquad 4.5$$

to fulfill the above criterion.

Using Wechsler's equation, the following sample radii required to make the sample boundary effects negligible are estimated for different thermal diffusivity values: (t = 200 s)

THERMAL DIFFUSIVITY (m^2/s)	SAMPLE RADIUS (mm)
1.0×10^{-7}	17.7
1.5×10^{-7}	21.7
2.0×10^{-7}	25.0
5.0×10^{-7}	39.6
1.0×10^{-6}	55.9
1.5×10^{-6}	68.5

The thermal test cell used in this study can house a specimen up to 1.5 in (38.1 mm) in radius. Therefore, in order for the test cell to be applicable to samples with higher thermal diffusivity values, the test time may have to be shortened to about one minute. It should be noted, however, that Wechsler's criterion only gives a general guideline which may be conservative for some applications. As long as the sample dimensions and the test time are selected such that sufficient data points are collected before the sample boundary effects become prominent, the thermal conductivity test apparatus and procedure are considered to be appropriate.

4.2.2.2 Design Problems and Rectifying Measures

Before proceeding to the discussion on other peripherial laboratory equipment; the problems encountered during actual thermal testing using the newly devised thermal test cell are worth mentioning.

One of the major problems with the thermal test cell (Figure 3.11) was the breakage of the ceramic base block during removal of the confining tube from the steel base after a test sequence. After the first occurrence of such breakage, it was suspected that the curing procedure for the ceramics was improper. Several attempts had been made to cure the insulating blocks. However, breakage of the blocks persisted during dismantling of the test apparatus. It was then realized that it was not the curing procedure that caused the problem. Although possessing a low thermal conductivity as desired, the ceramic block was just too brittle to withstand the high tensile stress developed when the cell was dismantled.

The use of Teflon as an insulating material was onced considered as a replacement for ceramics. However, the idea was discarded because of the high compressibility of Teflon. Besides, Teflon has a tendency to creep rather substantially at elevated temperatures. This is not desirable as every attempt is made to minimize disturbance to the test specimen.

Roulon-A, having lower thermal conductivity and compressibility than those of Teflon, was finally selected as the insulating material. The Roulon-A cap and base block are found to work remarkably well.

The breakage of the thin (1/8 inch) porous ceramic stone under high compressive loads also poses as a problem. The use of thicker (1/4 inch) porous stones had been attempted. Although the stones sometimes remained intact after a test sequence, breakage still occurred at other times. It was suggested that stronger metallic porous stones be used instead, but this would defeat the purpose of insulating the specimen from heat loss through the ends. It is anticipated that the metallic stones would act as heat sinks transmitting heat from the ends of the specimen to the external confining cylinder. At present, a more suitable type of low thermal conductivity porous stone with high compressive strength has not yet been located. Therefore, the 1/4-inch porous ceramic stones have been used for the latter part of the testing program.

Serious problems were also encountered during thermal conductivity testing as the internal probe broke frequently. Five probes were used for this study because of intermittent rupturing of the probes. Most of the probe failures occurred at the tip. In the last case, after proper sealing of the tip by plasma welding, the probe ruptured at the junction of the internal thermocouple and the mid-section of the probe wall. Again, plasma welding was employed to attach the thermocouple to the probe wall. No further problem was experienced.

The five probes used were made exactly the same way except that they are of two different lengths. The adequacy of probes of the first heated length (5.75 in) for thermal conductivity testing has been checked in the previous section. It would be prudent to check if the other probe length met the design criteria outlined earlier as follows:

1. Given heated length of new probe = 4.56 in (115.9 mm),

the L/d_o ratio is 36.5, which is considerably greater than 25 to account for negligible axial flow error.

2. Equation 4.2 is used to evaluate the maximum test time allowable to ensure that the radial flow assumption is justified. Listed below is the maximum test time calculated for each different thermal diffusivity value:

THERMAL DIFFUSIVITY (m^2/s)	MAX. TEST TIME (s)
1.0×10^{-7}	2122
2.5×10^{-7}	849
5.0×10^{-7}	424
7.5×10^{-7}	283
1.0×10^{-6}	212
1.5×10^{-6}	141

Since sufficient data points (on the linear portion of a temperature rise versus natural logarithm of time plot) can be gathered for thermal conductivity evaluation before the maximum test time specified above is reached, the radial flow assumption can easily be satisfied.

The above checks have indicated the acceptability of the new probe for further thermal conductivity measurements. The new apparatus can be used with confidence.

4.2.3 Power Supply to Thermal Conductivity Probe

To ensure a constant source of heat generated by the thermal conductivity probe in the transient state thermal test cell, a *dc* power supply is used. This Hewlett-Packard HP-6438B power supply unit is capable of generating a voltage of 60 V and an electric current of 3 A maximum. Both the voltage and the current can be varied by the coarse and fine tuning knobs on the unit.

A switch box, which includes a 2.0 Ω (1 % precision) resistor for the calculation of the electric current passing through the heat source system, has been made and is placed in series with the power supply unit as well as the probe heater. A schematic diagram of the overall circuitry for the heat source generating system is delineated in Figure 4.3. Sample calculations of the electric current and the power generated at the probe are included in Appendix D.

4.2.4 Temperature Controller for Silicon Rubber Heating Jacket

The silicon rubber heating jacket at the exterior of the thermal test cell is used for thermal diffusivity testing. External sample temperature can be varied by dialing the single set-point control knob on the temperature controller, which monitors the heating jacket temperature. The microprocessor-based control box includes a relay that is wired through a 15 ampere circuit breaker. The relay responds to feedback from one of the three thermocouples connected at the exterior of the test cell. The set-point temperature (from ambient temperature to 800 °F) is maintained by the alternatively switching on and off of the electric heating elements in the heating jacket. The temperature controller is manufactured by the Barber Colman Company. A sketch of the temperature control system for the silicon rubber heating jacket is shown in Figure 4.4.

4.2.5 Axial Loading System

Axial loading in the triaxial test apparatus (Figure 4.2; Agar, 1984) is applied through a hydraulic ram to the top of the sample. The ram is powered by a servo-controlled hydraulic pump. A vertical load of up to 440 kN may be generated. Either a constant load or a constant rate of straining may be set by the servo-controller. The servo power console Model SPC-1000 is manufactured by Structural Behavior Engineering

Laboratories.

4.2.6 Pore Pressure Injection System

A low pressure injection system (with nitrogen over silicon oil) as shown in Figure 4.5 is used as pressure source for applications from 0 to 4 MPa. A back pore fluid pressure of about 2 MPa is generally applied to maintain gases in solution within the test specimen. For pressure applications up to 27 MPa, a higher pressure system which includes a constant pressure air-actuated diaphragm pump (Figure 4.6) may be employed.

4.2.7 Hot Water or Steam Generator

A hot water or steam generator of 1900 ml capacity (Figure 4.7) is used as a hot water or steam source to the test specimen. The stainless steel generator is heated by electrical steel heating jackets that cover the exterior surface of the unit. Pressurized hot water or steam of temperatures up to 200 °C may be introduced into the sample during testing.

4.2.8 Data Acquisition System

Output signals from the thermocouples and the electronic transducers of the thermal testing system are scanned, processed and recorded by a Hewlett-Packard HP-3054DL data logging system. The system includes a HP-3497A data acquisition unit, a HP-85 microcomputer and a

HP-82901M flexible disc drive unit. All signals are converted to engineering units of temperature (°C), pressure (kPa), load (kN), displacement (mm), volume (ml), etc. by the microcomputer. Thermal test data are stored in floppy discs for later retrieval and analysis.

4.3 Sample Preparation and Mounting Procedures

4.3.1 Steady State Tests

Only dry and water-saturated samples of quartz sand (20-30 mesh) were tested using the steady state hot plate apparatus (Figure 4.1). Prior to sample preparation, the surface of the base plate as well as that of the heater plate were coated by a thin film of Dow Corning silicon heat sink compound. The grease was used to enhance the thermal contacts between the sample and the surfaces of the top and base plates.

The dry sample was prepared by compacting layers of the sand into the 15 cm diameter sample holder until the desired sample thickness was attained. Approximately 200 grams of the quartz sand was placed into the holder each time. A 15.2 cm diameter by 1.1 cm thick wooden spacer block was then placed flat on the top layer of sand inside the holder. With a cylindrical (7.36 cm diameter by 15.24 cm height) steel weight of about 5088 grams on top of the spacer block, the holder was shaken steadily on a vibrating table. The sand sample was allowed to compact under vibration by the dead weight for approximately one minute. A new layer of sand was then poured into the holder for further compaction until the final thickness was reached. The vibrating table (Model VP51D1) is manufactured by SYNTRON.

Water saturated sand samples were prepared the same way as for dry sand except that distilled water was used to saturate the sand before compaction by vibration. Distilled water was first mixed with about 200 grams of dry sand. The mixture was then stirred to ensure that any entrapped air was expelled as air bubbles. The wet sand was subsequently compacted the same way as described above. The vibration also helped in driving out any entrapped air that might still be present in the sample after the mixing and stirring process.

When the desired sample thickness was attained, the heater plate was placed on top of the sample. The entire sample holder was then put inside the insulated box (Figure 4.1). Thermocouples were inserted into the holes provide at the surfaces of the heater and the base plate. Other connections to the constant temperature cooling water bath , the Hewlett-Packard HP-6438B power supply, and the data acquisition system were subsequently made.

4.3.2 Transient State Tests

Prior to sample preparation, two rubber O-rings were greased (with Dow Corning high vacuum silicon grease) and placed in the grooves around the stainless steel base platen. The 'O'-rings were used to seal the sample from any fluid or pressure leakage to the exterior of the cell. A porous stone, with a 1/8 inch hole drilled at centre and a 1/16 inch hole to the side of it, was then slided down the central probe and thermocouple to the top of the ceramic base block. Dow Corning silicon heat sink compound was used to grease the surfaces of the probe assembly for better thermal contact with the sample.

Dry and water-saturated quartz sand and oil sand tailings sand were prepared in the transient state thermal test cell (Figure 3.11) the same way as described in the previous section. The same steel cylinder was used as dead weight, and a layer of about 200 grams of sand was compacted each time.

In the case of a remoulded oil sand sample, the as-received core sample was first left in room temperature to thaw prior to being crumbled to a uniform mass. The remoulded mass was then compacted in layers (of about 200 grams) in the sample confining tube by dropping the cylindrical weight from a fixed height of about 25 to 75 mm. The dead weight has a 6.2 mm diameter hole drilled along the longitudinal axis so that the weight can slide freely along the internal probe and thermocouple. The number of weight drops per layer of the sample should be the same but it may be varied for different samples to achieve variations in porosity or density.

Preparation of an undisturbed oil sand sample requires special attention and procedures. To minimize the disturbance of the sample due to gas exsolution and thawing, the undisturbed oil sand sample was prepared in a climate controlled cold room. The cold room is maintained at -20 °C. The selected frozen core sample was pre-chilled in a container by dry ice (-80 °C) for 24 hours prior to the actual trimming. The specimen diameter of 76 mm was achieved by trimming the sample with a diamond-tipped trimming bit on a lathe. The required length of core (152 mm) was notched from the core using a carbide steel notching bit and then cut out by a diamond saw. Final trimming of the diameter and the ends of the specimen were accomplished by remounting the sample on the lathe in a custom-designed chuck and finishing with a square carbide bit.

With a 76 mm diameter metal template placed on top of one end, the trimmed core sample was set up in a chuck to have a 6.4 mm (0.25 in) hole drilled along the longitudinal axis with a stainless steel drill bit. The metal template has a 3.2 mm diameter hole pre-drilled at its centre for alignment purpose. The finished sample was then mounted onto the base platen of the thermal test cell. To accomplish this, the sample was slided along the interior wall of the confining cylinder (76 mm i.d.) down to the base platen, where a piece of porous stone had already been placed on top of the ceramic base block. The central thermal conductivity probe and the thermocouple would protrude into the centre hole of the sample. The void between the central probe and the sample was backfilled with dry oil sand tailings sand which has the same thermal properties as the major mineral component (quartz sand) of the oil sand sample. The sand was poured down the void space by means of a narrow funnel. The sand was allowed to settle in the central hole and be compacted under vibration on a vibrating table. The density of the dry sand was calculated to be around 1.7 g/cm^3. When water saturated, the sand should have a density close to that of the undisturbed oil sand sample (around 2 g/cm^3).

Since the external diameter (73 mm) of the undisturbed lean oil sand core was less than the internal diameter (76 mm) of the confining cylinder, two new external thermocouples were used for thermal diffusivity measurements on the specimen. The thermocouples (at 180° apart) were mounted on the wall of the confining cylinder such that their tips protruded out of the interior wall to touch the sample surface. The void space between the external sample surface and the interior wall of the confining tube was backfilled with dry pulverized sand from the same oil sand deposit. The sand was compacted on a vibrating table.

Upon completion of the backfilling procedure, The top porous stone, ceramic and stainless steel caps were located on top of the specimen to form a complete seal from the external environment. The completed thermal test cell was subsequently mounted on the trolley-mounted triaxial cell base and wheeled to the laboratory.

In the laboratory, the triaxial cell base on which sat the thermal test cell and test specimen was jacked up and screwed into the confining triaxial cell wall. The entire triaxial cell assembly was then moved to the loading frame by means of a hydraulic crane. The necessary connections for the thermocouples, external LVDT, back pressure and loading systems as well as the data logging system were made.

To make full use of the oil sand samples, remoulded or undisturbed, each sample was tested under three conditions:

1. air-water-bitumen saturated (either as-prepared or nitrogen flushed),
2. water-bitumen saturated (with air displaced by injection of water), and
3. water-bitumen saturated (with new bitumen/water saturations after hot water flushing).

4.4 Saturation of Sample

To avoid fluid from boiling and entrapped air in solution from exsolving, nitrogen gas was introduced into the as-prepared remoulded or undisturbed oil sand samples. The nitrogen gas was pressurized to about 2 MPa which was sufficient to serve the purpose. To saturate the quartz sand, tailings sand or oil sand samples with water, pressurized water was injected through the lower drainage ports of the thermal test cell to displace air inside the samples. A back pore fluid pressure of about of 2 MPa was generally applied to the samples to maintain gases in solution.

4.5 Hot Water Flushing to Reduce Bitumen Content

The hot water or steam generator (Figure 4.7) was used to provide hot water for flushing bitumen out of the oil sand samples. About five pore volumes of hot water were generally used to reduce to oil saturation by 30 to 50 %.

4.6 Thermal Testing Procedures

The procedures for both the steady state and the transient state thermal property testings are rather simple. As mentioned previously, one of the major disadvantages of steady state testing is that it requires a few hours of test time as compared to a maximum of about 10 minutes for transient state thermal testing.

4.6.1 Steady State Thermal Conductivity Testing

The cooling water bath temperature is set at several degrees (e.g. 5 °C) below room temperature while the *dc* power supply unit is adjusted to yield a hot plate temperature of a few degrees above room temperature. As thermal equilibrium of the system is attained after a few hours, thermocouple readings at the heater and base plates are recorded for analysis.

4.6.2 Transient State Thermal Conductivity Testing

The cartridge heaters at the exterior triaxial cell wall (Figure 4.2) are used to maintain the desired ambient temperature. The silicon rubber heating jacket covering the thermal test cell may be utilized to help fine tuning the surface temperature of the test specimen. Constant or variable vertical loads may be applied to the top of the sample to simulate vertical confining pressure. The rate of loading is controlled by the servo-control unit. Pore pressures are applied to the sample to simulate reservoir fluid pressure and to maintain gases in solution at elevated temperatures.

As thermal equilibrium is reached, the thermal conductivity test can be started by simply switching on the power supply to the central thermal conductivity probe. The starting time should be synchronized with the time when the data logging system begins to take scans of measurements at intervals of 15 seconds. The external temperature of the sample does not change during the test. The time history of temperature rise of the central thermal conductivity probe is recorded by the internal thermocouple. Among the data to be recorded are the external and internal sample temperatures as well as the voltages across the 2 Ω resistor and the power supply unit.

4.6.3 Transient State Thermal Diffusivity Testing

The triaxial test cell and the thermal test cell are both heated up and pressurized the same way as in a thermal conductivity test. When thermal equilibrium of the system is attained, the temperature of the silicon rubber heating jacket is set by the temperature controller at about 20 °C (36 °F) above the ambient temperature. Both the external surface temperature and the internal temperature of the sample are monitored by thermocouples and are recorded by the data logging system at 20-second intervals.

It was found that approximately 5 seconds after the start of the test were required for the heat front to travel from the heating jacket to the external sample surface through the steel confining tube. To compensate for this time lag, the incremental temperature was introduced 5 seconds in advance of the first data scan taken by the data logging system. This procedure ensured that the external surface temperature of the sample would begin to rise immediately after time zero, as recorded by the data logger at 20-second intervals.

4.6.4 Average Sample Temperature Reporting

Since the thermal testing procedures require that the test specimen be heated, the average temperature of the sample may increase slightly during the tests. In order to investigate the magnitude of this sample temperature increase, two computer programs were coded.

The program for average temperature calculations during a thermal conductivity test is based on the ideal line source equation (3.8). Temperatures at various radial distances from the internal thermocouple to the external surface of the sample are calculated. The average temperature per unit length of the sample is computed with respect to its cross-sectional area. It is noted that at an average test time of about 100 seconds, the average sample temperature only increases by about 0.1 to 0.5 °C above the ambient temperature. Therefore, it should not be crude to simply report the average sample temperature as the ambient test temperature during a thermal conductivity test.

A similar computer program was written for the evaluation of average sample temperature during a thermal diffusivity test. The increase in average sample temperature is dependent on the thermal diffusivity of the material. Listed below are rough estimates of the temperature increments, that should be added to the test temperatures, for different thermal diffusivity values. The average test time was taken to be about 120 seconds.

THERMAL DIFFUSIVITY (m^2/s)	INCR. TEMP. (°C)
$1.0x10^{-7}$	1
$1.5x10^{-7}$	1
$2.0x10^{-7}$	2
$2.5x10^{-7}$	2
$5.0x10^{-7}$	2
$7.5x10^{-7}$	3
$1.0x10^{-6}$	3
$1.5x10^{-6}$	4

It should be noted that the thermal diffusivity (temperature) equation (3.23) involves the summation of infinites series. Since the present computer system has an upper limit to the order of magnitude of exponents, only the first 56 terms of all infinite series summations involving Bessel functions and the temperature function (equation 3.23) were used. The approximation was found to be adequate for the purpose of thermal diffusivity determination. However, as the radial distance varies from the inner radius to the external radius of the sample, the approximation of Bessel functions becomes quite crude. This renders the evaluation of average sample temperature an inherent error. More terms in the infinite series may have to be used for better approximation, but the present upper limit of exponentiation does not allow this modification. Nevertheless, the current program for approximating an average sample temperature during a thermal diffusivity test should be adequate if only a rough estimate of the temperature is required. The test temperature of a thermal diffusivity test is thus reported as the sum of the ambient temperature and the corresponding temperature increment listed above.

4.7 Testing Program

Table 4.1 outlines the thermal testing program followed during this research. It has been established that the steady state hot plate apparatus (Cervenan, Vermeulen and Chute, 1981) is capable of producing thermal conductivity values of dry materials with reasonable accuracies (± 2 %) at room temperature and atmospheric pressure conditions. Therefore, to calibrate the transient state thermal test cell used in the current research, steady state tests on a dry quartz sand were performed under various cooling water bath and heater temperatures. Subsequent thermal tests were performed using the thermal test cell on quartz sand, tailings sand and oil sand samples at various temperatures. Bitumen/water proportions and degrees of saturation of the oil sand specimens were also varied for a study of the effects of such changes on the thermal properties.

As previously mentioned, the testing program was interrupted intermittently by the rupturing of the thermal conductivity probe inside the thermal test cell. A second probe of slightly shorter heated length was used after the first occurrence of such failures. A thermal conductivity test was performed on a dry quartz sand specimen for re-calibration purpose. The result was found to be comparable to what was obtained from previous testing.

During thermal testing of the undisturbed medium oil sand sample, the new thermal conductivity probe was ruptured. The testing sequence was thus interrupted. A third probe, which is identical to the second one, was subsequently set up for further testing. However, the breakage of the tip of this probe during pressurization of the sample stopped the progress. Based on the fact that all probe failures occurred at the tip, it is believed that the original design of the probe by WATLOW (St. Louis) is not meant for testing under high pressures. Stress concentration occurred at the tip of the probe where a thin metal disc was inserted. Another supplier, ALLTEMP SENSORS (Edmonton), recommended that the tip of such probe be cut off and be sealed by plasma welding. Following the recommendation, two already-purchased probes from WATLOW were modified. The probes are identical to the first one used for this study. The testing program was subsequently continued. Unfortunately, this new probe again cracked, but this time at the junction of the internal thermocouple tip and the mid-section of the probe. It was suspected that the probe surface was weakened by the silver soldering for thermocouple attachment to the probe wall. The fifth probe was subsequently modified with plasma welding both at the tip and at the thermocouple-probe junction. The probe was also dried in an oven at 100 °C for several hours to remove any moisture that might be present inside. A water-saturated tailings sand specimen was then prepared for thermal conductivity and diffusivity measurements at room temperature condition. The results obtained are compatible to the first series of tests on the sand. This final testing assembly was then used for thermal testing of the last (undisturbed lean oil sand) sample.

4.8 Coding of Thermal Property Tests

Since over two hundred thermal property measurements were performed on a total of twelve samples for this research, the test specimens and test numbers have to be labelled according to a consistent coding system for ease of identification. The steady state and transient state test coding methods are described as follows:

Steady State

Since only thermal conductivity tests on dry and water-saturated quartz sand samples were performed using the hot plate apparatus, the coding may only involve average test temperature, sample height and saturation condition for identification purpose. A typical specimen code is described below:

HPT-1.5-20D

The first notation specifies that this is a **H**ot **P**late **T**est. The second designation denotes a sample thickness of 1.5 inches (38 mm). Average test temperature is at 20 °C. The sample is **D**ry. For a water-saturated sample, an **S** is used.

Transient State

The coding of a transient state property test is more complicated than that of a steady state one. The notations possibly required are listed as follows:

NOTATIONS:

R(remoulded), **U**(undisturbed) (for oil sands only)

QS(quartz sand), **TS**(tailings sand) or **OS**(oil sand)

sample number(**1**,**2** or **3**) (for quartz sand only)
R(rich), **M**(medium) or **L**(lean) (for oil sand only)

C(conductivity) or **D**(diffusivity)

average test temperature (20 to 200 °C)

D(dry) or **S**(water-saturated)
(for quartz sand & tailings sand only)
A(air-water-bitumen saturated),
W(water-bitumen saturated) or
F(water-bitumen saturated, after flushing)
(for oil sand only)

test number for same sample at approximately
the same temperature (1, 2, 3, 4)
(for quartz sand & tailings sand only)

UD(undrained) or blank(drained)
(for saturated tailings sand & oil sand only)

EXAMPLES:

1. QS2-C20S-4-UD
2. TS-D100D-2
3. ROSL-C50A
4. UOSR-D200F

EXPLANATIONS:

1. Quartz Sand sample #2; Conductivity test at 20 °C; Water-saturated; Test #4 at this temperature; Undrained conditions.
2. Tailings Sand; Diffusivity test at 100 °C; Dry; Test #2 at this temperature; Drained conditions.
3. Remoulded Oil Sand; Lean; Conductivity test at 50 °C; Air-water-bitumen saturated; Drained conditions.
4. Undisturbed Oil Sand; Rich; Diffusivity test at 200 °C; Flushed, water-bitumen saturated; Drained conditions.

4.9 Index Testing

To characterize the different test specimens used in this research, their physical properties were established by various index tests. These tests include the determination of bulk density, moisture content, bitumen and water saturations as well as grain size distribution.

The bulk density of a remoulded test specimen (i.e. dry and water-saturated quartz sand and tailings sand, and remoulded oil sand) was determined by weighing the specimen and measuring its volume as it was being prepared. In the case of an undisturbed oil sand sample, the bulk density was determined by weighing and direct volume measurement on the final trimmed core. Moisture contents of sand samples were determined after testing while bitumen and water contents of oil sand samples (remoulded or undisturbed) were determined both before and after testing. Standard bitumen extraction procedure (Method #2.7 outlined by Syncrude Canada Limited, 1979) was followed. The bitumen extraction apparatus used in this study is identical to the one described in Agar's (1984) thesis. ASTM standard method of grain size distribution analyses (D402-72) were performed on all test specimens.

Table 4.1 Thermal Testing Program

Material	Number of Thermal Tests			Saturation Condition		Remarks
	Steady State Conductivity	Transient State Cond.	Transient State Diff.	Dry	Partial or Full	
Quartz Sand	27	-	-	*		For comparison with transient state test results at room temperature.
	27	-	-		*	
Quartz Sand	-	10	-	*		For comparison with steady state test results at room temperature; Also for study of sensitivity of conductivity to varying voltage inputs.
	-	10	-		*	
Tailings Sand	-	1	-	*		Test temperature at 20°C
	-	8	6		*	Test temperatures at 20°C, 50°C, 100°C, 150°C and 200°C.
Quartz Sand	-	14	6	*		Ditto.
Remoulded Oil Sand, Rich	-	11	15		*	Ditto.
Quartz Sand	-	1	1	*		Ditto; For calibration of new probe.
Remoulded Oil Sand, Lean	-	11	11		*	Test temperatures at 20°C, 50°C, 100°C, 150°C and 200°C.
Undisturbed Oil Sand, Medium	-	4	6		*	Ditto.
Undisturbed Oil Sand, Rich	-	8	15		*	Ditto.
Tailings Sand	-	1	1		*	Ditto; For calibration of new probe.
Undisturbed Oil Sand, Lean	-	10	10		*	Test temperatures at 20°C, 50°C, 100°C, 150°C and 200°C.

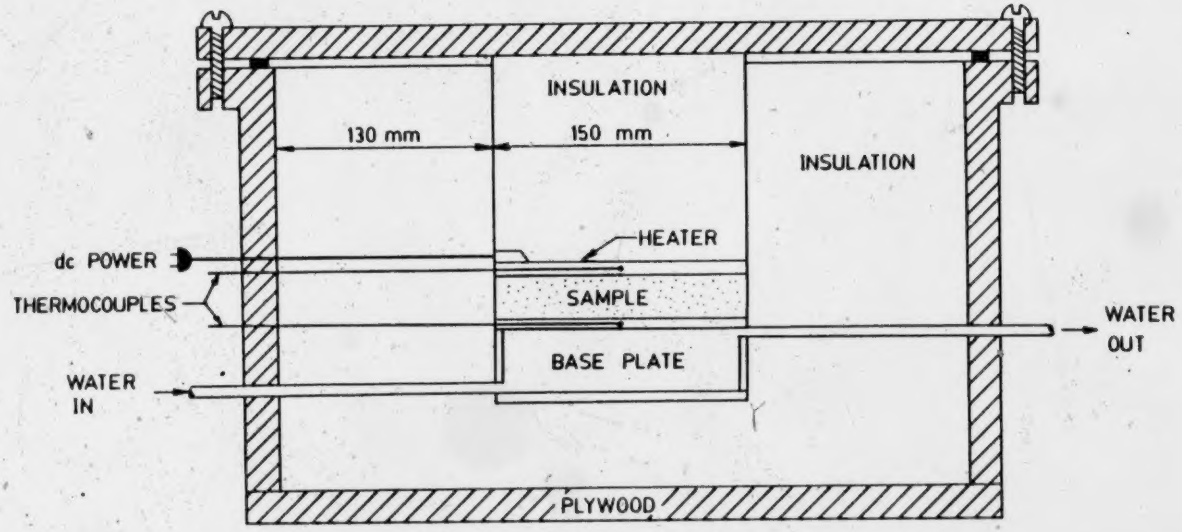


Figure 4.1 Hot Plate Apparatus used by Cervenan, Vermeulen and Chute, 1981

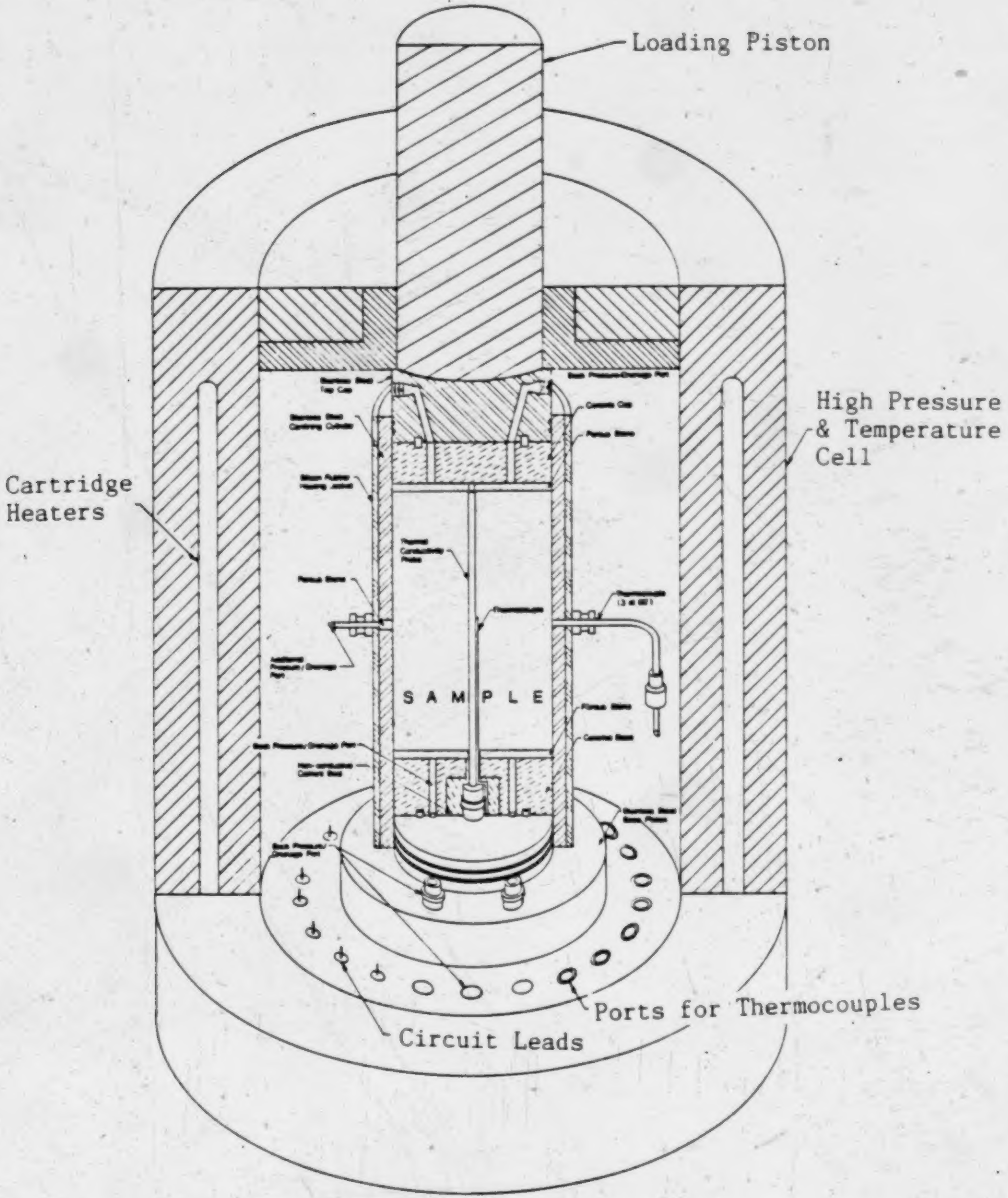
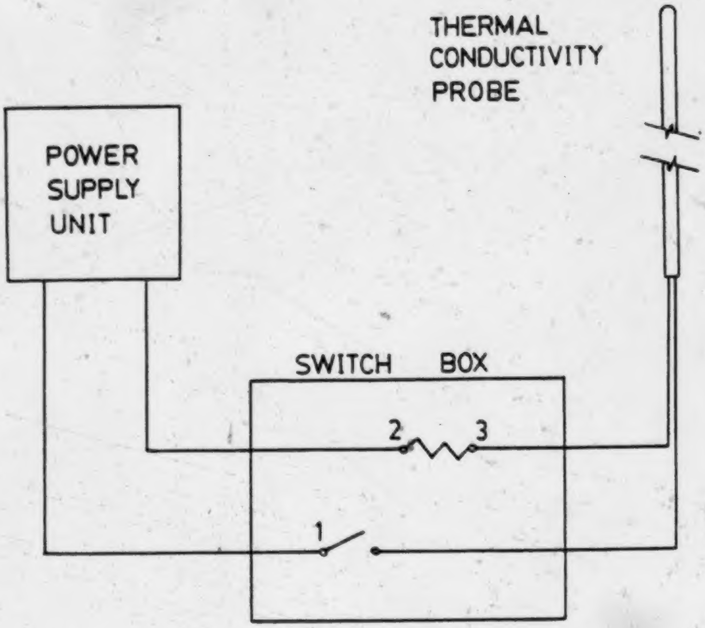


Figure 4.2 High Pressure and Temperature Triaxial Compression Test Cell



1-2 CONNECTED TO DATA ACQUISITION UNIT FOR MEASURING VOLTAGE ACROSS POWER SUPPLY UNIT

2-3 CONNECTED TO DATA ACQUISITION UNIT FOR MEASURING VOLTAGE ACROSS RESISTOR

Figure 4.3 Schematic Diagram of Power Supply to Thermal Conductivity Probe

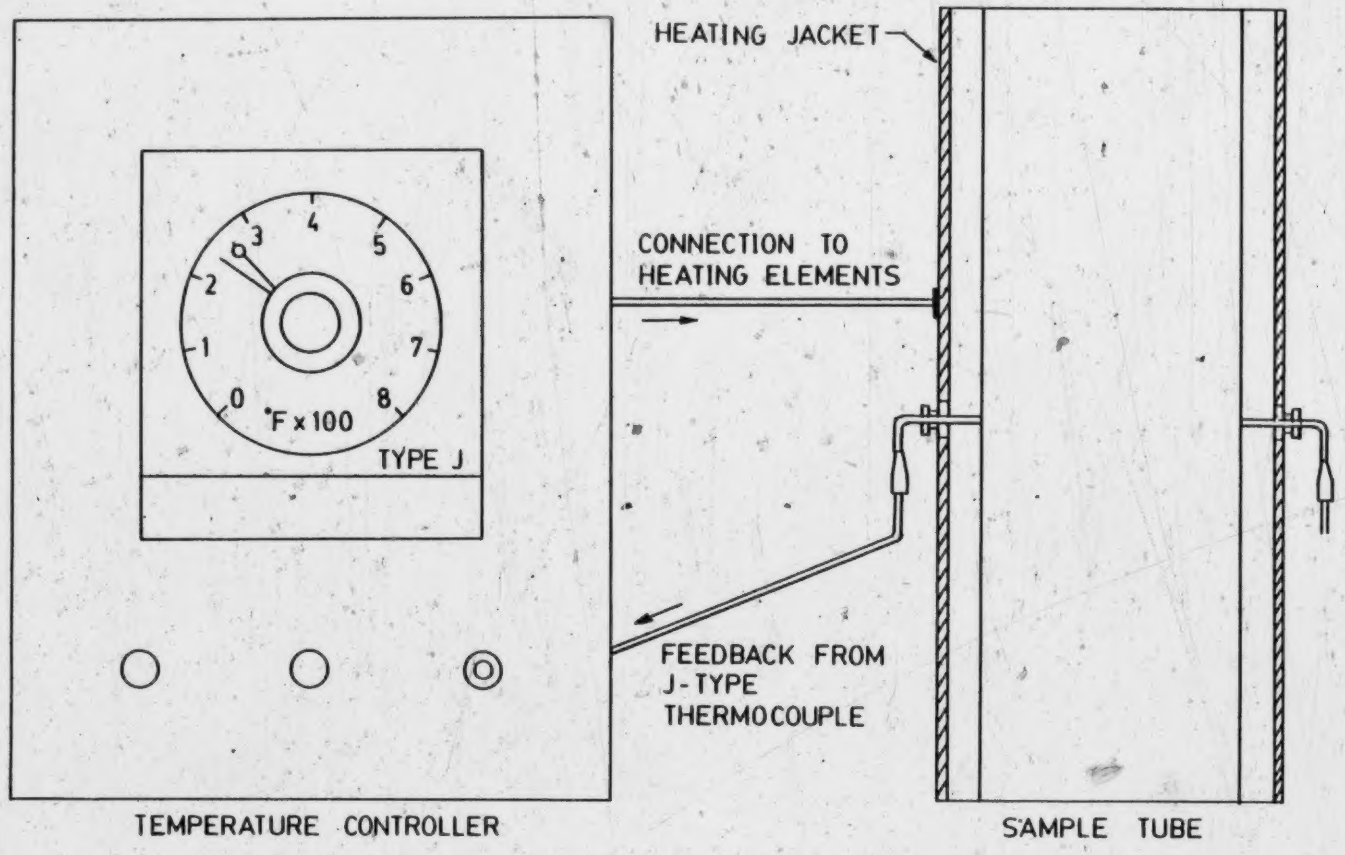


Figure 4.4 Sketch of Temperature Controller and Silicon Rubber Jacket Connections

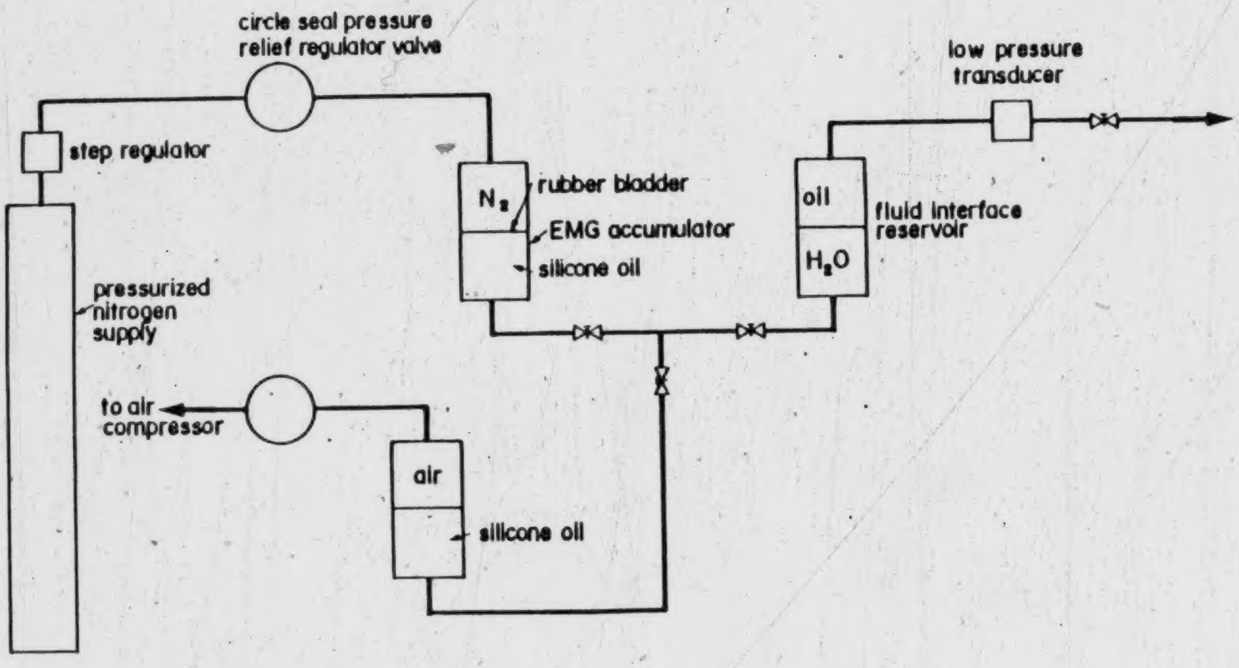


Figure 4.5 Schematic Diagram of Low Pressure System (after Agar, 1984)

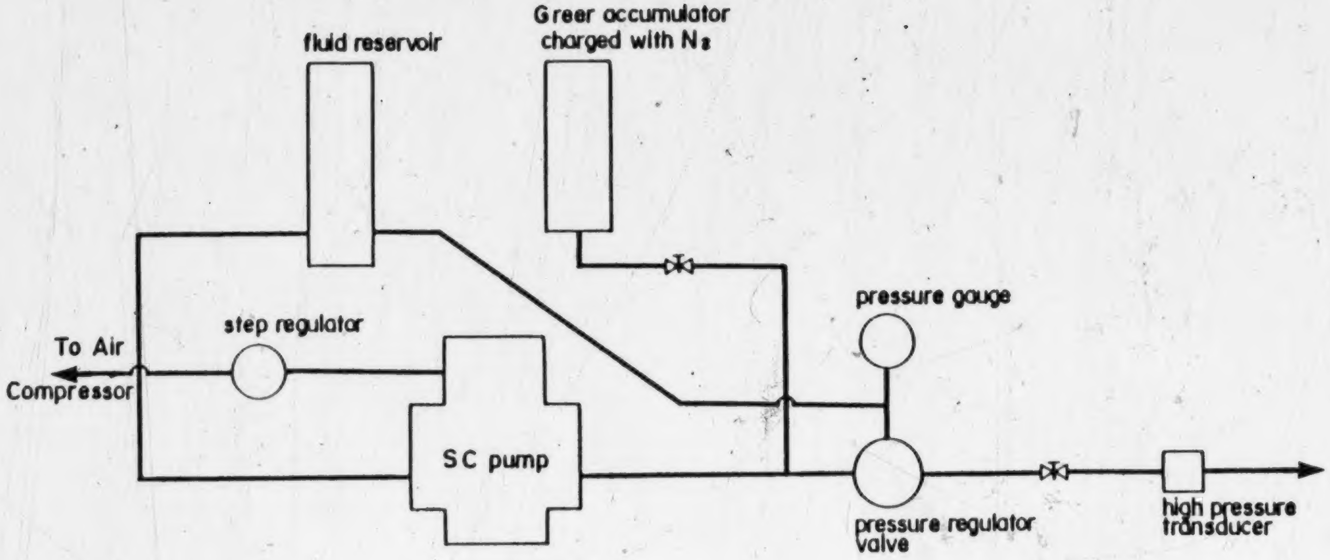


Figure 4.6 Schematic Diagram of High Pressure System (after Agar, 1984)

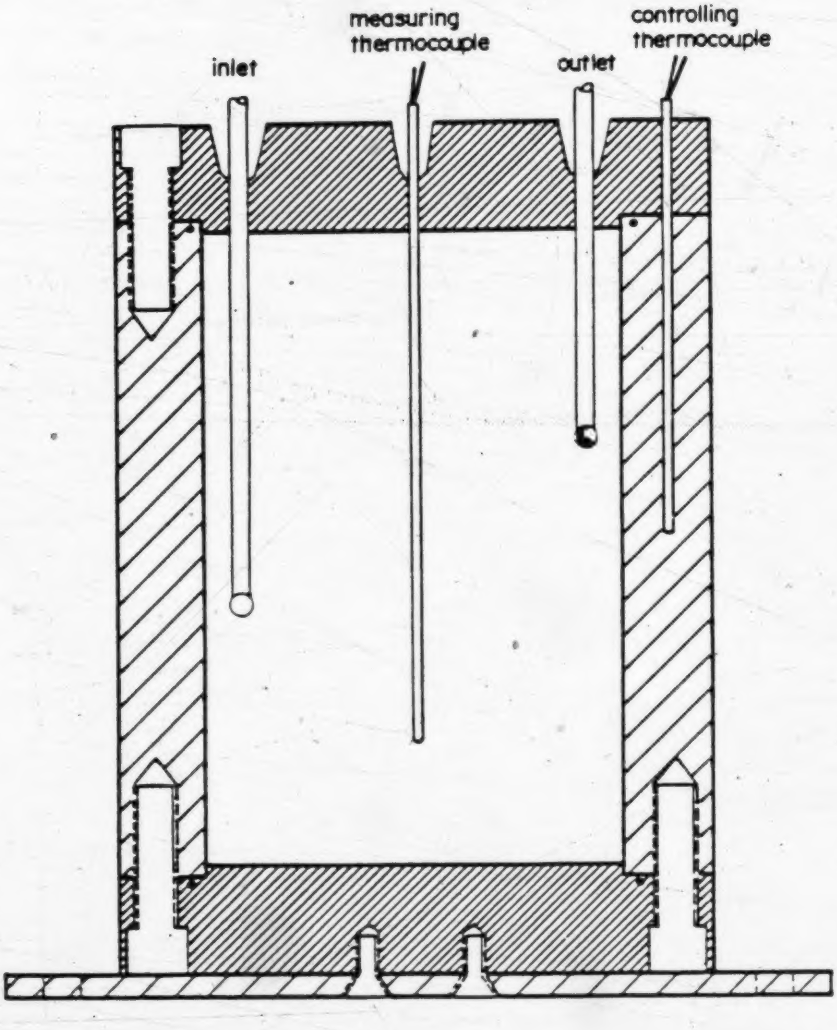


Figure 4.7 Hot Water or Steam Generator (after Agar, 1984)

5. RESULTS OF LABORATORY TESTING

5.1 Analysis of Laboratory Results

The proposed methods of analysis for transient state thermal conductivity and diffusivity tests were discussed in Chapter 3. Thermal conductivity of a test specimen is determined from the slope of the straight line portion of a temperature versus natural logarithm of time plot. Thermal diffusivity may be estimated from the temperature axis intercept of the same plot. Alternatively, thermal diffusivity of the same specimen may be determined more accurately by a thermal diffusivity test. A multiple linear regression analysis is used to establish a seventh order polynomial for the representation of the sample surface temperature record. Using the surface temperature function and the temperature-time record of the internal thermocouple, thermal diffusivity values are evaluated for each time increment (20 seconds) by the *regula-falsi* iteration procedure.

Analysis of steady state thermal conductivity test results is also described in Chapter 3 and will not be detailed here.

5.2 Specific Heat Calculations

According to equation 3.7, the specific heat of a material may be calculated if its density, thermal conductivity and diffusivity are known. Both the thermal conductivity and diffusivity values of a sample can be established experimentally and the initial volume and mass are measured. With the change in sample height monitored during thermal testing, the change in volume of the mass can be determined rather easily. Assuming that the mass of the specimen stays constant even during thermal testing under drained conditions, densities of the specimen at various temperatures are then calculated. The assumption is reasonable because the loss of bitumen to drainage lines, as monitored by the volume change device during testing, is negligible when compared to the bulk mass of the sample. In the presentation of laboratory results that follows, estimated specific heat values are given for samples with both thermal conductivity and diffusivity values established experimentally. Sample calculations of density change with temperature for a test specimen are included in Appendix D.

As discussed in Chapter 2, many investigators (e.g. Smith-Magowan, Skauge and Hepler, 1982) agree that the specific heat of a material may be estimated with reasonable accuracy by taking the weighted average of the specific heats of its constituents. Using Smith-Magowan, Skauge and Hepler's correlation equations, specific heats of the samples tested for this study are calculated by the weighted average method. The values are included in the tables of results that follow. Sample specific heat calculations are included in Appendix D.

5.3 Thermal Properties of Quartz Sand

Since the thermal conductivity of quartz sand is quite well documented and since quartz sand is the major constituent of Athabasca oil sands, quartz sand has been tested both under steady state and transient state conditions.

5.3.1 Test Material

The sand is a 20-30 (mesh) Ottawa sand supplied from Ottawa, Illinois. The main constituent of the medium to coarse sand is quartz particles. Some negligible traces of foreign minerals are also present in the sand mass. A grain size distribution curve showing the results of a sieve analysis on the sand is included in Appendix E.

5.3.2 Experimental Results

Steady state thermal conductivity test results on dry and water-saturated quartz sand samples are summarized in Tables 5.1 and 5.2 respectively. In order to account for thermal contact resistance between the hot/cold plate surface and the specimen, determination of thermal conductivity requires test results from samples of at least three different thicknesses. Figure 5.1 shows plots of thermal resistance versus sample thickness for the dry and water-saturated quartz sands at room temperature. Thermal conductivity values are determined from the slopes of the straight line plots using equation 3.5. Thermal resistance of the apparatus is determined by the intercept at the vertical axis of Figure 5.1. The value is noted as 0.11×10^{-2} and 0.20×10^{-2} m^2 °C/W for the dry and water-saturated sand samples respectively.

Depending on the thickness of the test specimen, the average test (or sample) temperature may vary even if the same power supply and water bath temperature are used during a steady state hot plate test. The difference in sample thickness (L_2-L_1) incurs a natural adjustment of the hot plate temperature (T_2) in order to maintain a constant thermal gradient (dT/dL) across the same material (equation 3.3). Without a knowledge of the magnitude of the temperature change when samples of different thicknesses were tested, different levels of power supply and temperature range were used. It was planned that the same average temperature for specimens of different thicknesses, but of the same material, could be achieved. A thermal resistance versus thickness plot could then be made for thermal conductivity determination.

As may be noted from Tables 5.1 and 5.2, the deviations in the average temperatures of the specific tests selected for thermal conductivity determination at room temperature are only 1.5 °C in the dry quartz sand case and 0.3 °C for the saturated sand. The densities of the samples are also similar enough for the purpose of thermal conductivity determination.

As the results may not be too accurate for tests with average temperatures higher than laboratory temperature, thermal conductivities of the dry and water-saturated sand specimens are not determined at temperatures other than room temperature. The values obtained from room temperature testing will be used for comparisons with the corresponding transient state test results.

Transient state thermal conductivity test results of a dry and subsequently water-saturated quartz sand sample (QS1) at 20 °C, using various voltage inputs generated by the power supply unit, are presented in Figure 5.2. To study the effects of temperature on the thermal conductivity and diffusivity of dry quartz sand, another dry quartz sand specimen (QS2) was tested at various temperatures ranging from room temperature to about 200 °C. The results are tabulated in Table 5.3. Plots depicting the change in thermal conductivity and thermal diffusivity of dry quartz sand with temperature are shown in Figures 5.3 and 5.4 respectively. The thermal conductivity and diffusivity test results for the dry quartz sand sample (QS3) used for calibration of the new probe heater (of different length of heated section) are summarized below:

Voltage = 20 V
ρ = 1.782 g/cm^3
n = 32.8 %
k = 0.446 W/m °C (at 21 °C)
α = 3.3x10^{-7} m^2/s (at 22 °C)
c = 0.76 J/g °C (calculated; equation 3.7)

It is found that the thermal conductivity of this quartz sand sample (QS3) is comparable to that of the first sample (QS1) which has a similar density.

5.4 Thermal Properties of Tailings Sand

One dry oil sand tailings sand specimen was tested for thermal conductivity determination using the transient state cell. The sample was then saturated with water. Both thermal conductivity and diffusivity tests were subsequently carried out at various temperatures up to 200 °C. All but two tests were performed under fully drained conditions.

5.4.1 Test Material

The sand is a clean poorly sorted fine to medium quartz sand obtained from the Syncrude tailings pond in Alberta. The origin of the sand is from the Athabasca oil sand deposits. The solids consist of about 2% fines (finer than #200 sieve). Results of a sieve analysis on the sand is included in Appendix E.

5.4.2 Experimental Results

Table 5.4 summarizes the thermal test results of the tailings sand. Changes in thermal conductivity and diffusivity with temperature are depicted in Figures 5.5 and 5.6 respectively. The thermal conductivity and diffusivity test results for the extra water-saturated tailings sand sample, used for re-calibration of the fifth probe, are summarized below:

Voltage = 20 V
ρ = 2.081 g/cm^3
n = 34.4 %
k = 3.143 W/m °C (at 22 °C)
α = 15.4x10^{-7} m^2/s (at 26 °C)
c = 0.98 J/g °C (calculated; equation 3.7)

5.5 Thermal Properties of Oil Sands

Transient state thermal conductivity and diffusivity tests were performed on two remoulded oil sand and three undisturbed oil sand specimens. As mentioned earlier (Section 4.7), some of the proposed testing sequences were interrupted by breakage of thermal conductivity probes. Nevertheless, sufficient thermal property data of oil sands have been collected for evaluation of the developed testing procedure. Physical properties of the oil sand and tailings sand samples are tabulated in Table 5.5.

5.5.1 Test Material

The medium to rich oil sand core samples (remoulded or undisturbed) were obtained by rotary drilling at a site near a slope bank of Saline Creek, Fort McMurray, Alberta. The lean oil sand cores were taken from the Syncrude site in Fort McMurray. Sieve analyses on samples from these two sources were performed. The grain size distribution curves are included in Appendix E.

5.5.2 Experimental Results

Thermal property test results for the rich and lean remoulded oil sand samples (ROSR and ROSL) as well as the medium, rich and lean undisturbed oil sand cores (UOSM, UOSR and UOSL) are summarized in Tables 5.6 to 5.10 respectively. Changes in thermal conductivity and diffusivity with temperature for each of the samples are plotted as shown in Figures 5.7 to 5.16. A typical set of thermal conductivity and diffusivity test data from 20 °C to 200 °C (sample ROSR) are presented graphically in Appendix F.

As may be noted from the tabulated results, the remoulded oil sand samples were first tested as-prepared. The degree of saturation as well as water and bitumen saturations were determined prior to the testing sequence. Therefore, these values are applicable to the air-water-bitumen saturated condition. As water was injected into the test system for full water-bitumen saturation of the sample, it is assumed that air inside the sample was displaced by water. Therefore, the bitumen saturation did not change. Upon completion of the entire testing sequence, the water and bitumen contents of the sample were again measured. If the sample had been flushed with hot water to reduce the bitumen content for the final stage of testing, the saturations measured are assumed to apply to this last testing condition.

All undisturbed oil sand samples were fully saturated by displacing air out with water prior to thermal property measurements. The initial air voids are assumed to be filled with water after saturation. Therefore, the water and bitumen contents of each specimen were known at the beginning of the testing sequence. Hot water flushing was employed to reduce the bitumen content for a second stage of testing of the rich oil sand specimen. Nitrogen was injected into the thermal test cell to displaced some of the water out at room temperature for the final stage of testing of this sample as well as the lean one. It is assumed that negligible amount of bitumen was expelled out of the sample during nitrogen-flushing because of the high viscosity of bitumen at room temperature. Hence, the measured bitumen content at the end of the test sequence applies to the last two stages of tests. This means that bitumen contents of the undisturbed lean oil sand sample under full water-bitumen saturated and nitrogen-flushed conditions should be the same, both before and after the testing sequence. Within the limits of experimental errors in the bitumen extraction procedures, the results shown in Table 5.5 indicate that this is true.

To determine the amount of water that was displaced by nitrogen during nitrogen-flushing of a specimen, a measuring cylinder was used to collect water from the exit at the bottom drainage port of the high temperature/pressure cell. Sample calculations of air, water and bitumen saturations for the oil sand samples are included in Appendix D.

Table 5.1 Summary of Hot Plate Test Results, Dry Quartz Sand

Test	Average Test Temperature °C	Power Input W	Temperature Difference °C	Apparent Thermal Conductivity W/m °C
Sample 1: 27 mm thick; density = 1.805 g/cm^3; porosity = 31.9 %				
HPT-1-19D*	19.0	1.98	6.91	0.400
HPT-1-24D	23.8	4.54	15.70	0.426
HPT-1-30D	30.5	8.08	28.00	0.425
HPT-1-23D	23.0	2.02	7.00	0.425
HPT-1-28D	27.8	4.54	15.60	0.429
HPT-1-34D	34.4	8.08	27.40	0.434
HPT-1-27D	27.0	2.02	6.70	0.441
HPT-1-32D	31.6	4.54	15.10	0.443
HPT-1-38D	38.1	8.06	26.80	0.443
Sample 2: 13 mm thick; density = 1.806 g/cm^3; porosity = 31.8 %				
HPT-0.5-32D	31.6	8.08	13.37	0.424
HPT-0.5-28D	27.9	4.54	7.50	0.425
HPT-0.5-25D	25.3	2.02	3.23	0.439
HPT-0.5-28D	27.6	8.08	13.60	0.417
HPT-0.5-24D	24.0	4.54	7.80	0.409
HPT-0.5-21D	21.2	2.00	3.50	0.400
HPT-0.5-24D	23.8	8.06	13.85	0.408
HPT-0.5-20D*	19.9	4.34	7.60	0.400
HPT-0.5-17D	17.4	2.01	3.65	0.386
Sample 3: 39 mm thick; density = 1.789 g/cm^3; porosity = 32.5 %				
HPT-1.5-42D	42.4	8.08	35.70	0.485
HPT-1.5-34D	34.2	4.63	20.50	0.484
HPT-1.5-28D	28.0	2.01	8.80	0.490
HPT-1.5-39D	38.8	8.08	36.40	0.476
HPT-1.5-30D	30.3	4.54	20.65	0.472
HPT-1.5-24D	24.1	2.01	9.34	0.461
HPT-1.5-35D	35.0	7.99	36.85	0.465
HPT-1.5-27D	26.7	4.53	21.56	0.450
HPT-1.5-21D*	20.5	2.02	10.18	0.425

* Data selected for thermal conductivity evaluation.

Table 5.2 Summary of Hot Plate Test Results, Water-saturated Quartz Sand

Test	Average Test Temperature °C	Power Input W	Temperature Difference °C	Apparent Thermal Conductivity W/m °C
Sample 1: 27 mm thick; density = 2.119 g/cm^3; porosity = 31.7 %				
HPT-1-27S	26.7	8.10	3.54	3.374
HPT-1-23S	22.6	8.12	3.60	3.326
HPT-1-19S	18.6	8.12	3.65	3.280
HPT-1-29S	28.7	12.72	5.77	3.252
HPT-1-25S	24.7	12.68	5.85	3.195
HPT-1-21S	20.8	12.68	5.88	3.178
HPT-1-30S	30.1	15.32	7.25	3.115
HPT-1-26S	26.0	15.32	7.29	3.098
HPT-1-22S*	22.1	15.32	7.34	3.077
Sample 2: 38 mm thick; density = 2.156 g/cm^3; porosity = 32.2 %				
HPT-1.5-27S	27.3	8.08	4.93	3.454
HPT-1.5-23S	23.4	8.06	5.03	3.376
HPT-1.5-19S	19.4	8.06	5.10	3.330
HPT-1.5-30S	29.9	12.90	8.00	3.399
HPT-1.5-26S	25.8	12.60	7.87	3.374
HPT-1.5-22S*	21.8	12.60	7.93	3.348
HPT-1.5-31S	31.2	15.29	9.56	3.370
HPT-1.5-27S	27.2	15.29	9.61	3.353
HPT-1.5-23S	23.2	15.26	9.70	3.316
Sample 3; 51 mm thick; density = 2.128 g/cm^3; porosity = 32.1 %				
HPT-2-28S	28.0	8.08	6.36	3.513
HPT-2-24S	23.9	8.08	6.48	3.562
HPT-2-20S	20.0	8.08	6.60	3.475
HPT-2-26S	25.9	4.54	3.55	3.601
HPT-2-22S*	21.8	4.54	3.70	3.455
HPT-2-18S	17.9	4.54	3.75	3.409
HPT-2-27S	26.8	6.18	4.80	3.620
HPT-2-23S	22.9	6.18	4.95	3.510
HPT-2-19S	18.8	6.18	5.00	3.475

* Data selected for thermal conductivity evaluation.

Table 5.3 Thermal Conductivity and Diffusivity Test Results, Dry Quartz Sand

Test Number	Thermal Conductivity W/m °C	Thermal Diffusivity 10^{-7} m^2/s Calc.	Expt.	Density g/cm^3	Specific Heat J/g °C Expt.	Wt.Avg.Md.
QS2-C19D-1	0.545	2.5	-	1.737	0.80	0.76
QS2-C20D-2	0.493	2.0	-	1.737	0.73	0.76
QS2-C20D-3	0.497	2.2	-	1.737	0.73	0.76
QS2-C21D-4	0.509	2.2	-	1.737	0.75	0.76
QS2-C21D-5	0.507	2.1	-	1.737	0.75	0.76
QS2-C21D-6	0.503	2.1	-	1.737	0.74	0.76
QS2-C48D-1	0.529	2.4	-	1.734	0.82	0.81
QS2-C49D-2	0.512	2.2	-	1.736	0.80	0.81
QS2-C98D-1	0.550	2.3	-	1.729	0.91	0.87
QS2-C100D-2	0.522	1.7	-	1.731	0.86	0.87
QS2-C148D-1	0.539	2.0	-	1.721	1.01	0.92
QS2-C148D-2	0.541	2.3	-	1.724	1.01	0.92
QS2-C199D-1	0.555	2.3	-	1.720	1.01	0.96
QS2-C198D-2	0.552	2.2	-	1.716	1.01	0.96
QS2-D22D-1	-	-	3.9	1.737	-	-
QS2-D22D-2	-	-	3.9	1.737	-	-
QS2-D51D	-	-	3.7	1.736	-	-
QS2-D100D	-	-	3.5	1.731	-	-
QS2-D150D	-	-	3.1	1.724	-	-
QS2-D200D	-	-	3.2	1.716	-	-

Table 5.4 Thermal Conductivity and Diffusivity Test Results, Tailings Sand

Test Number	Thermal Conductivity W/m °C	Thermal Diffusivity 10^{-7} m²/s		Density g/cm³	Specific Heat J/g °C	
		Calc.	Expt.		Expt.	Wt.Avg.Md.
TS-C21D-1*	0.491	2.1	-	1.700	-	0.76
TS-C21S-1	3.340	10.0	-	2.059	1.07	1.30
TS-C22S-2-UD	3.298	9.2	-	2.059	1.06	1.30
TS-C21S-3	3.494	11.4	-	2.059	1.12	1.30
TS-C49S	3.145	8.5	-	2.054	1.13	1.34
TS-C100S-1	3.286	15.7	-	2.045	1.36	1.40
TS-C100S-2-UD	2.947	9.1	-	2.045	1.22	1.40
TS-C148S	2.776	15.0	-	2.037	1.25	1.45
TS-C198S	2.563	11.7	-	2.030	1.43	1.51
TS-D26S-1	-	-	14.8	2.059	-	-
TS-D26S-2	-	-	15.5	2.059	-	-
TS-D53S	-	-	13.5	2.054	-	-
TS-D103S	-	-	11.8	2.045	-	-
TS-D151S	-	-	10.9	2.037	-	-
TS-D202S	-	-	8.8	2.030	-	-

* Dry sample; Others water-saturated.

Table 5.5 Physical Properties of Oil Sand Samples

Sample	Saturation Code	Density g/cm^3	Porosity %	Constituents % by mass			Degree of Saturation %		
				Solids	Bitumen	Water	Overall	Bitumen	Water
ROSR	A	1.797	44.0	82.5	16.5	1.0	71.3	67.5	3.8
	W	1.943	-	77.1	15.4	7.5	100.0	67.5	32.5
	F	1.933	43.4	77.5	10.1	12.4	100.0	45.0	55.0
ROSL	A	1.775	41.8	85.3	4.0	10.7	62.5	16.9	45.6
	W	1.929	39.6	79.9	3.7	16.4	100.0	18.4	81.6
UOSM	W	2.073	35.0	83.2	12.3	4.5	100.0	73.0	27.0
	F	2.062	34.9	83.2	7.2	9.6	100.0	42.6	57.4
UOSR	W	2.085	34.3	83.6	14.7	1.7	100.0	89.4	10.6
	F	2.085	34.3	83.6	6.6	9.8	100.0	40.3	59.7
	A	1.973	34.3	88.3	7.0	4.7	67.5	40.3	27.2
UOSL	W	2.137	31.1	85.5	3.1	11.4	100.0	21.4	78.6
	A	2.104	29.3	89.0	2.2	8.8	78.8	15.9	62.9
TS	D	1.700	35.1	100.0	0.0	0.0	0.1	0.0	0.1
	S	2.059	33.1	84.3	0.0	15.7	100.0	0.0	100.0

Saturation Code:
A = Air-water-bitumen saturated
W = Water-bitumen saturated
F = Flushed, water-bitumen saturated
D = Dry
S = Water saturated

Table 5.6 Thermal Conductivity and Diffusivity Test Results, Rich Remoulded Oil Sand

Test Number	Thermal Conductivity W/m °C	Thermal Diffusivity 10^{-7} m²/s		Density g/cm³	Specific Heat J/g °C	
		Calc.	Expt.		Expt.	Wt.Avg.Md.
ROSR-C20A	1.281	6.6	-	1.797	0.81	0.91
ROSR-C21A	1.295	6.9	-	1.796	0.82	0.91
ROSR-C49A	1.231	5.6	-	1.795	0.87	1.01
ROSR-C99A	1.163	4.4	-	1.793	0.94	1.09
ROSR-C151A	1.114	4.0	-	1.791	1.07	1.16
ROSR-C199A	0.992	2.8	-	1.788	1.09	1.21
ROSR-D24A	-	-	8.8	1.796	-	-
ROSR-D52A	-	-	7.9	1.795	-	-
ROSR-D102A	-	-	6.9	1.792	-	-
ROSR-D154A	-	-	5.8	1.790	-	-
ROSR-D200A	-	-	5.1	1.788	-	-
ROSR-C20W	1.734	6.7	-	1.943	1.00	1.13
ROSR-C50W	1.664	13.0	-	1.941	1.07	1.21
ROSR-C101W	1.470	7.1	-	1.938	1.10	1.29
ROSR-C149W	1.336	5.5	-	1.934	1.11	1.36
ROSR-C198W	1.246	4.4	-	1.931	1.19	1.42
ROSR-D24W	-	-	8.9	1.934	-	-
ROSR-D53W	-	-	8.0	1.941	-	-
ROSR-D104W	-	-	6.9	1.938	-	-
ROSR-D152W	-	-	6.2	1.934	-	-
ROSR-D200W	-	-	5.4	1.931	-	-
ROSR-D24F	-	-	9.5	1.933	-	-
ROSR-D52F	-	-	8.7	1.930	-	-
ROSR-D103F	-	-	7.5	1.927	-	-
ROSR-D152F	-	-	6.6	1.924	-	-
ROSR-D200F	-	-	5.7	1.920	-	-

Table 5.7 Thermal Conductivity and Diffusivity Test Results, Lean Remoulded Oil Sand

Test Number	Thermal Conductivity W/m °C	Thermal Diffusivity 10^{-7} m^2/s		Density g/cm^3	Specific Heat J/g °C	
		Calc.	Expt.		Expt.	Wt.Avg.Md.
ROSL-C20A	1.522	5.0	-	1.775	0.95	1.15
ROSL-C21A	1.536	5.6	-	1.775	0.98	1.15
ROSL-C49A	1.520	4.5	-	1.776	1.04	1.21
ROSL-C98A	1.566	4.1	-	1.777	1.12	1.27
ROSL-C147A	1.684	4.0	-	1.778	1.23	1.33
ROSL-C196A	2.014	5.0	-	1.780	1.47	1.39
ROSL-D23A	-	-	9.0	1.775	-	-
ROSL-D24A	-	-	8.6	1.775	-	-
ROSL-D53A	-	-	8.2	1.776	-	-
ROSL-D101A	-	-	7.9	1.777	-	-
ROSL-D150A	-	-	7.7	1.778	-	-
ROSL-D199A	-	-	7.7	1.780	-	-
ROSL-C20W	2.216	4.5	-	1.929	1.30	1.35
ROSL-C49W	2.186	4.3	-	1.929	1.36	1.40
ROSL-C98W	2.073	3.7	-	1.931	1.42	1.46
ROSL-C147W	1.977	3.5	-	1.932	1.48	1.52
ROSL-C197W	1.817	3.0	-	1.933	1.52	1.59
ROSL-D23W	-	-	8.7	1.929	-	-
ROSL-D53W	-	-	8.5	1.929	-	-
ROSL-D100W	-	-	7.6	1.931	-	-
ROSL-D149W	-	-	6.8	1.932	-	-
ROSL-D199W	-	-	6.2	1.933	-	-

Table 5.8 Thermal Conductivity and Diffusivity Test Results, Medium Undisturbed Oil Sand

Test Number	Thermal Conductivity W/m °C	Thermal Diffusivity 10^{-7} m²/s		Density g/cm³	Specific Heat J/g °C	
		Calc.	Expt.		Expt.	Wt.Avg.Md.
UOSM-C20W	2.009	4.2	-	2.073	0.90	1.00
UOSM-C48W	1.850	3.1	-	2.071	0.94	1.08
UOSM-C98W	1.786	3.0	-	2.068	1.03	1.16
UOSM-C148W	1.747	3.0	-	2.065	1.18	1.22
UOSM-D22W	-	-	10.8	2.073	-	-
UOSM-D52W	-	-	9.5	2.071	-	-
UOSM-D101W	-	-	8.4	2.068	-	-
UOSM-D151W	-	-	7.2	2.065	-	-
UOSM-D200W	-	-	6.2	2.062	-	-
UOSM-D201F	-	-	7.0	2.062	-	-

Table 5.9 Thermal Conductivity and Diffusivity Test Results, Rich Undisturbed Oil Sand

Test Number	Thermal Conductivity W/m °C	Thermal Diffusivity 10^{-7} m²/s		Density g/cm³	Specific Heat J/g °C	
		Calc.	Expt.		Expt.	Wt.Avg.Md.
UOSR-C20W	1.765	3.9	-	2.085	0.76	0.92
UOSR-C48W	1.736	3.8	-	2.058	0.81	1.01
UOSR-C98W	1.659	4.9	-	2.051	0.93	1.09
UOSR-C148W	1.597	4.4	-	2.044	1.07	1.16
UOSR-C196W	1.500	4.4	-	2.037	1.19	1.21
UOSR-D24W	-	-	11.2	2.085	-	-
UOSR-D52W	-	-	10.4	2.058	-	-
UOSR-D101W	-	-	8.7	2.051	-	-
UOSR-D151W	-	-	7.3	2.044	-	-
UOSR-D199W	-	-	6.2	2.037	-	-
UOSR-C99F	2.026	6.8	-	2.051	0.99	1.27
UOSR-C147F	1.884	6.0	-	2.044	1.07	1.33
UOSR-C197F	1.730	5.3	-	2.037	1.16	1.39
UOSR-D25F	-	-	13.2	2.085	-	-
UOSR-D52F	-	-	12.0	2.058	-	-
UOSR-D102F	-	-	10.0	2.051	-	-
UOSR-D150F	-	-	8.6	2.044	-	-
UOSR-D200F	-	-	7.3	2.037	-	-
UOSR-D26A	-	-	14.6	1.973	-	-
UOSR-D52A	-	-	13.5	1.948	-	-
UOSR-D101A	-	-	10.3	1.941	-	-
UOSR-D151A	-	-	9.2	1.935	-	-
UOSR-D200A	-	-	8.4	1.928	-	-

Table 5.10 Thermal Conductivity and Diffusivity Test Results, Lean Undisturbed Oil Sand

Test Number	Thermal Conductivity W/m °C	Thermal Diffusivity 10^{-7} m^2/s Calc.	Expt.	Density g/cm^3	Specific Heat J/g °C Expt.	Wt.Avg.Md.
UOSL-C20W	2.676	5.8	-	2.137	0.94	1.17
UOSL-C48W	2.674	6.0	-	2.149	1.01	1.22
UOSL-C99W	2.560	6.1	-	2.169	1.07	1.29
UOSL-C148W	2.394	5.7	-	2.189	1.14	1.34
UOSL-C197W	2.391	5.4	-	2.220	1.25	1.40
UOSL-D23W	-	-	13.3	2.137	-	-
UOSL-D51W	-	-	12.3	2.149	-	-
UOSL-D102W	-	-	11.0	2.169	-	-
UOSL-D151W	-	-	9.6	2.189	-	-
UOSL-D200W	-	-	8.6	2.220	-	-
UOSL-C21A	2.778	12.1	-	2.104	0.99	1.08
UOSL-C49A	2.767	10.8	-	2.098	1.02	1.13
UOSL-C99A	2.551	7.2	-	2.090	1.13	1.19
UOSL-C149A	2.385	6.3	-	2.081	1.17	1.24
UOSL-C198A	2.477	6.3	-	2.073	1.36	1.30
UOSL-D25A	-	-	13.3	2.104	-	-
UOSL-D52A	-	-	12.9	2.098	-	-
UOSL-D102A	-	-	10.8	2.090	-	-
UOSL-D151A	-	-	9.8	2.081	-	-
UOSL-D200A	-	-	8.8	2.073	-	-

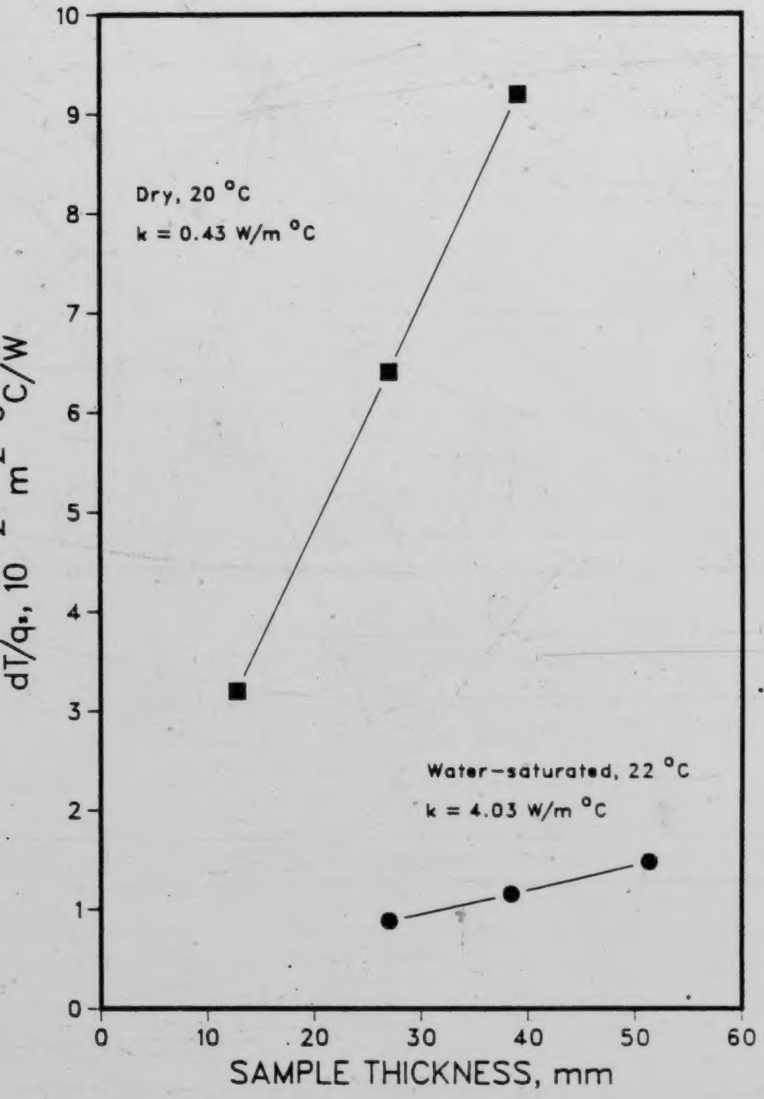


Figure 5.1 Hot Plate Thermal Conductivity Tests, Quartz Sand

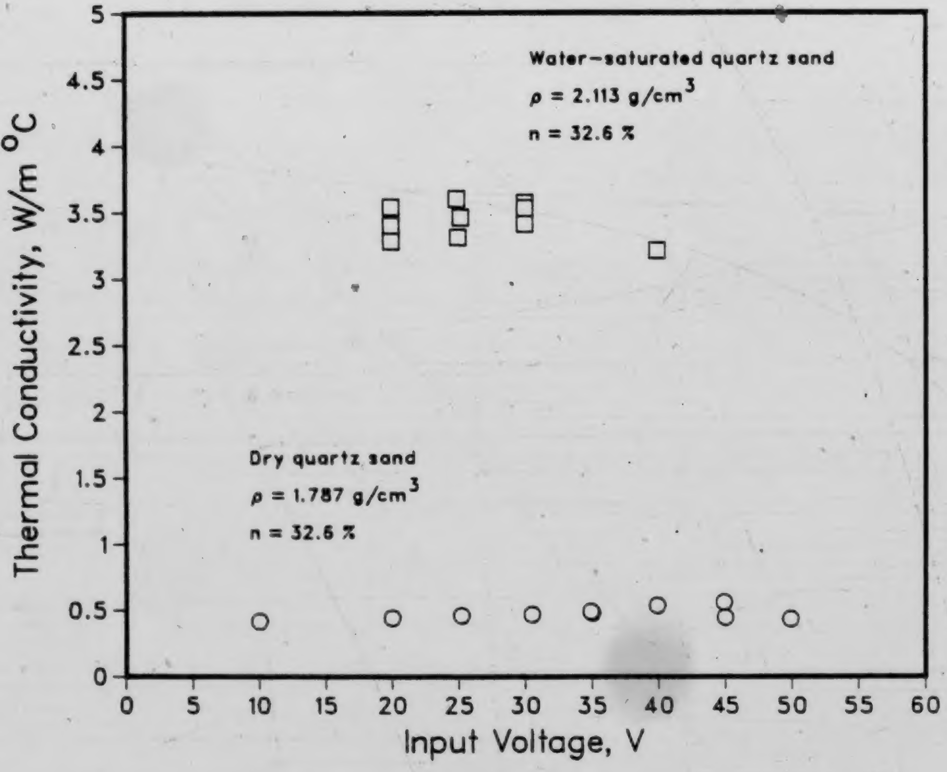


Figure 5.2 Sensitivity of Thermal Conductivity to Voltage Input

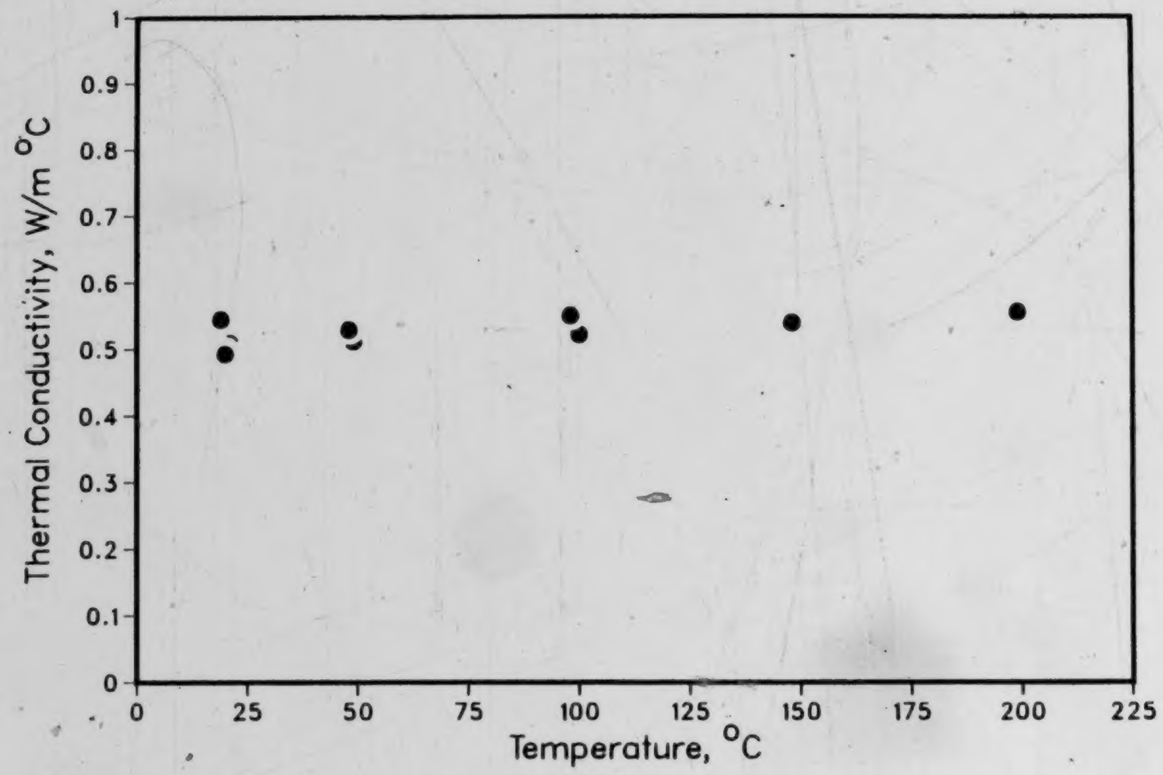


Figure 5.3 Change in Thermal Conductivity with Temperature, Dry Quartz Sand

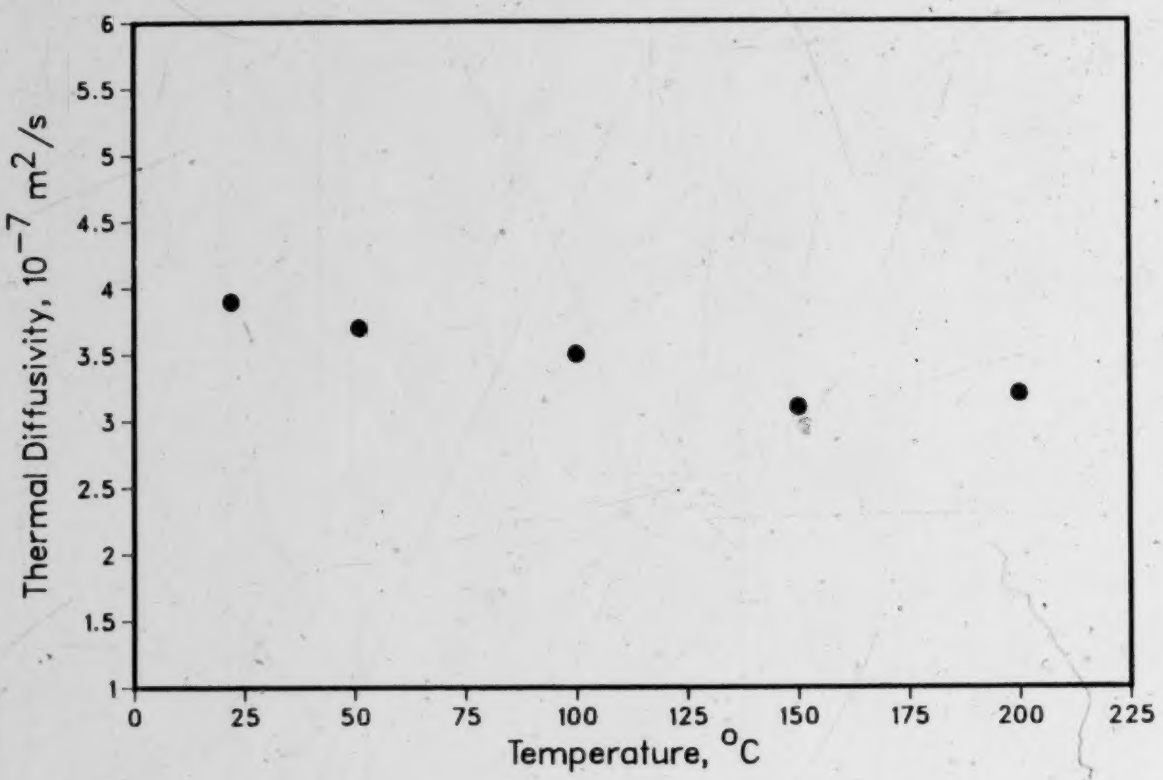


Figure 5.4 Change in Thermal Diffusivity with Temperature, Dry Quartz Sand

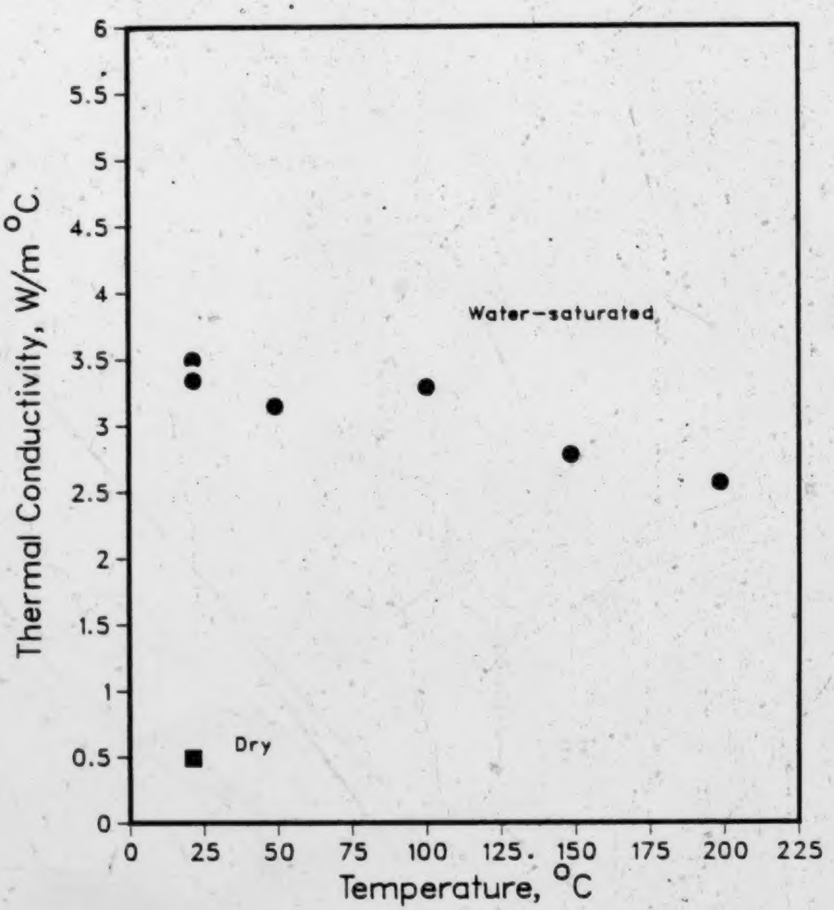


Figure 5.5 Change in Thermal Conductivity with Temperature, Tailings Sand

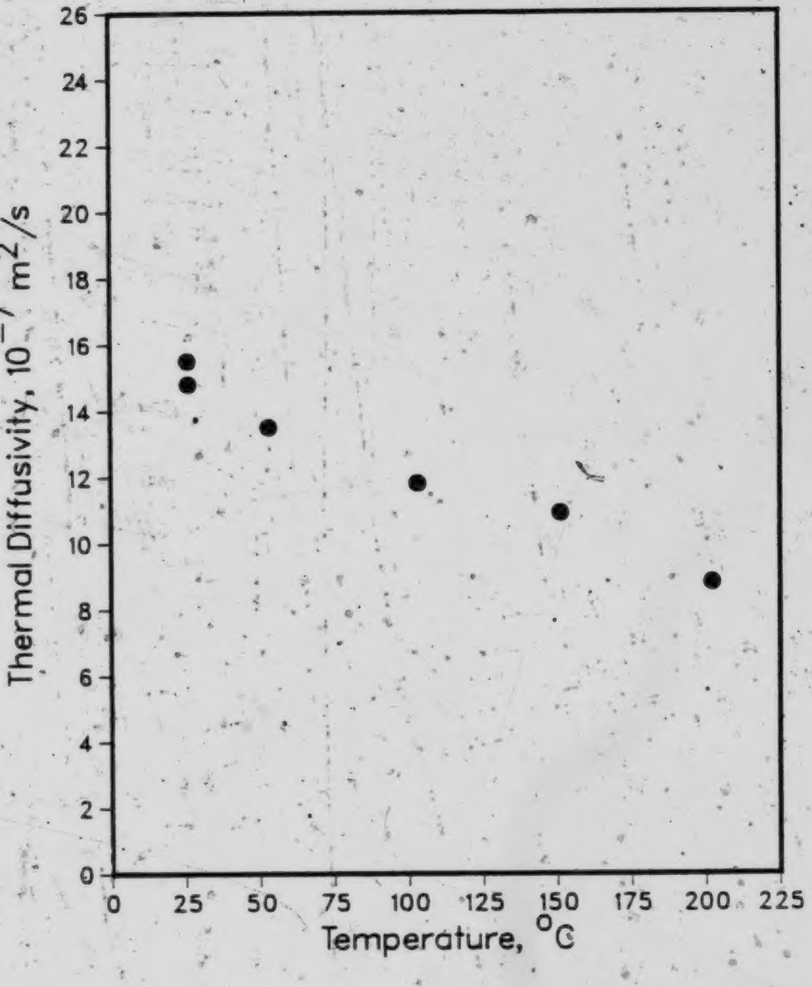


Figure 5.6 Change in Thermal Diffusivity with Temperature, Saturated Tailings Sand

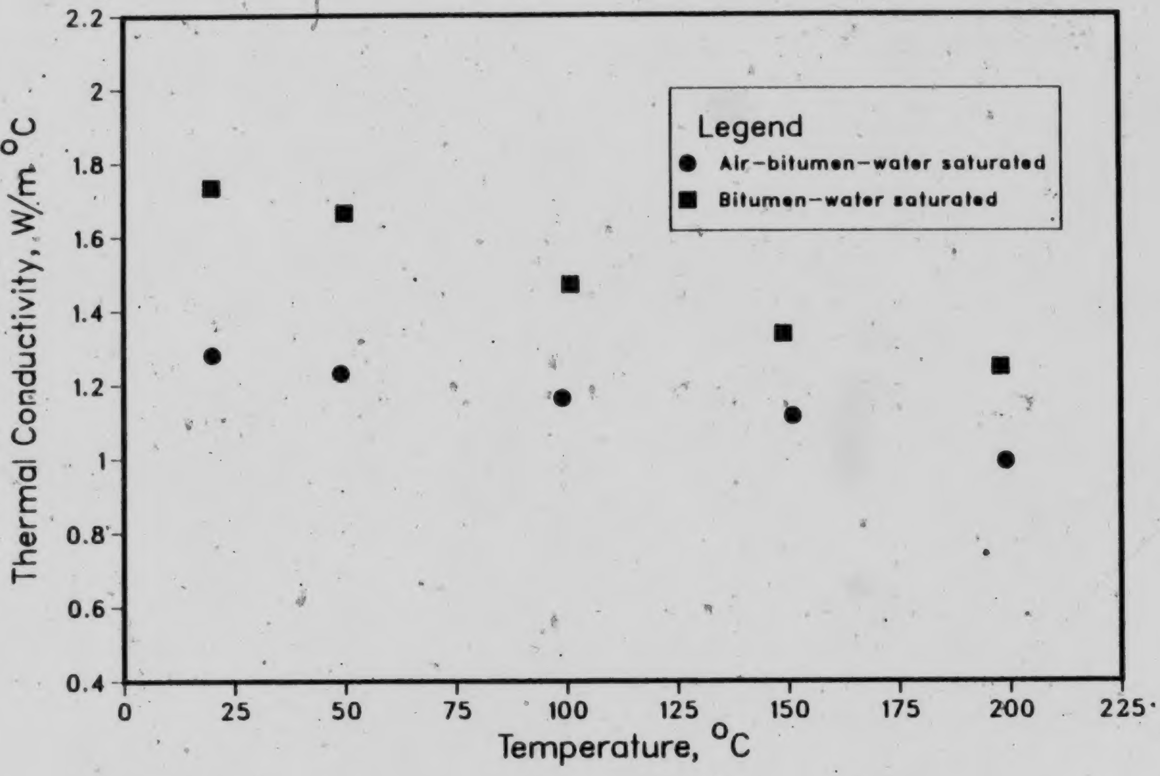


Figure 5.7 Change in Thermal Conductivity with Temperature, Rich Remoulded Oil Sand

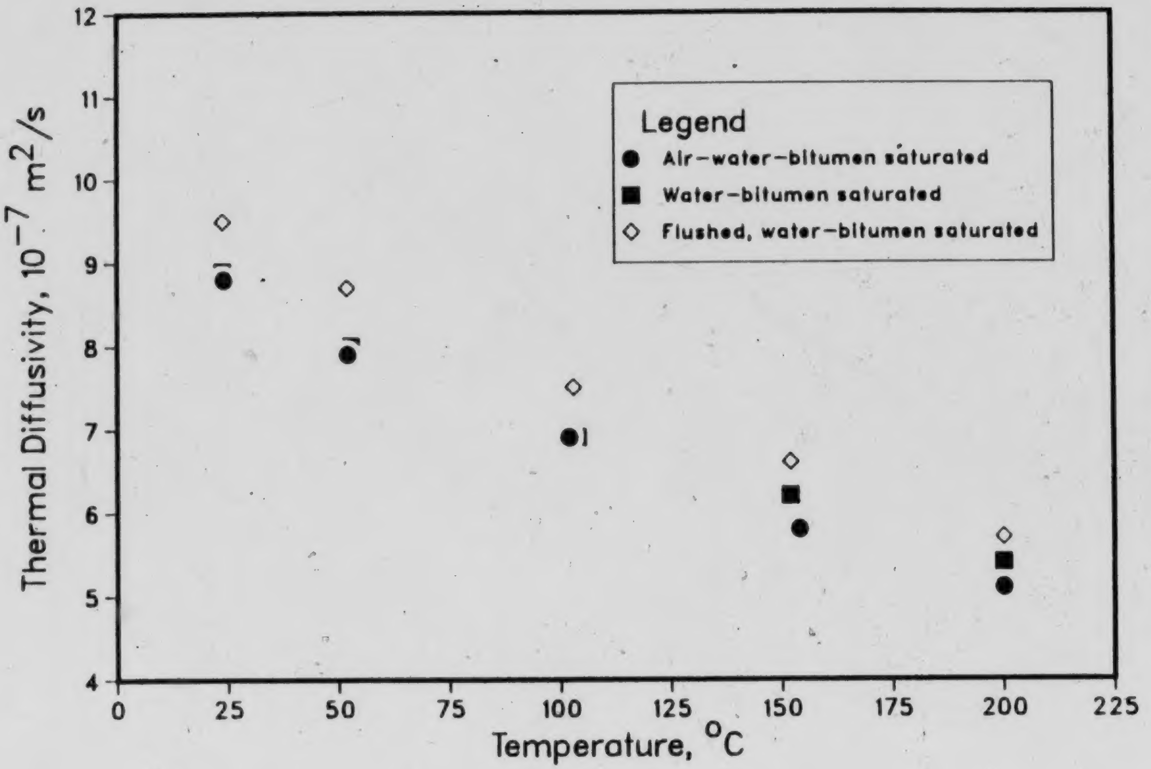


Figure 5.8 Change in Thermal Diffusivity with Temperature, Rich Remoulded Oil Sand

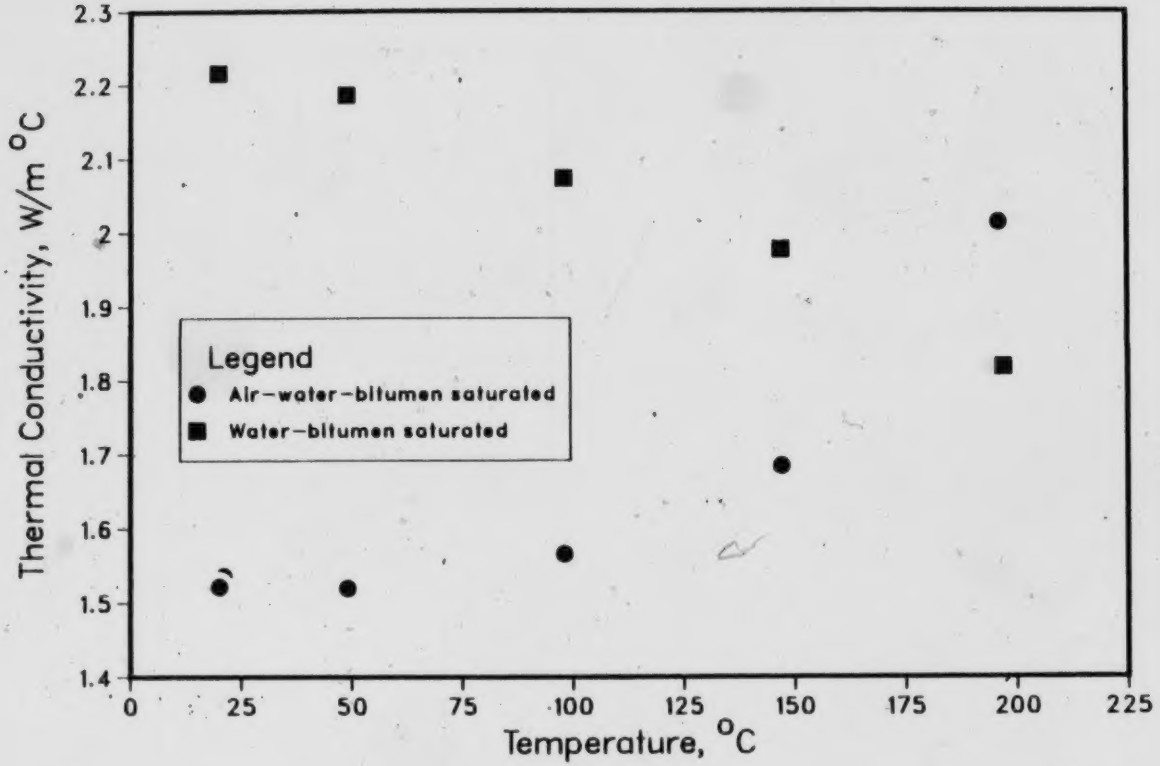


Figure 5.9 Change in Thermal Conductivity with Temperature,
Lean Remoulded Oil Sand

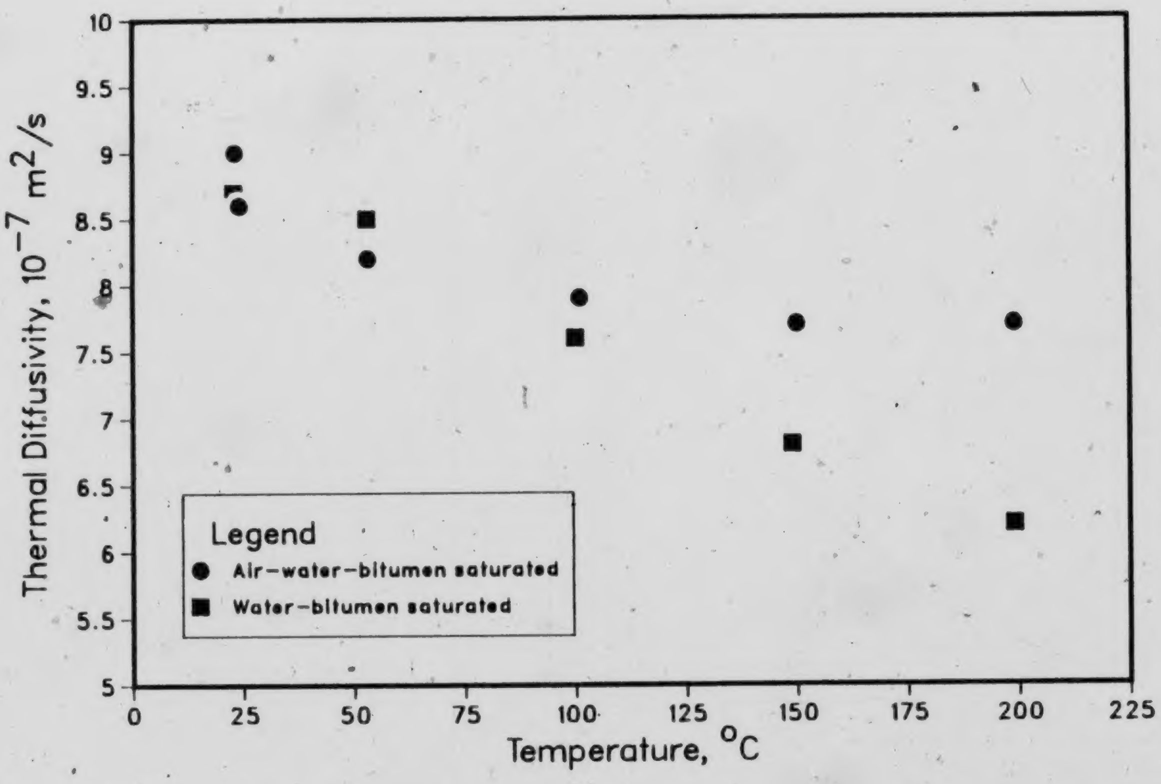


Figure 5.10 Change in Thermal Diffusivity with Temperature, Lean Remoulded Oil Sand

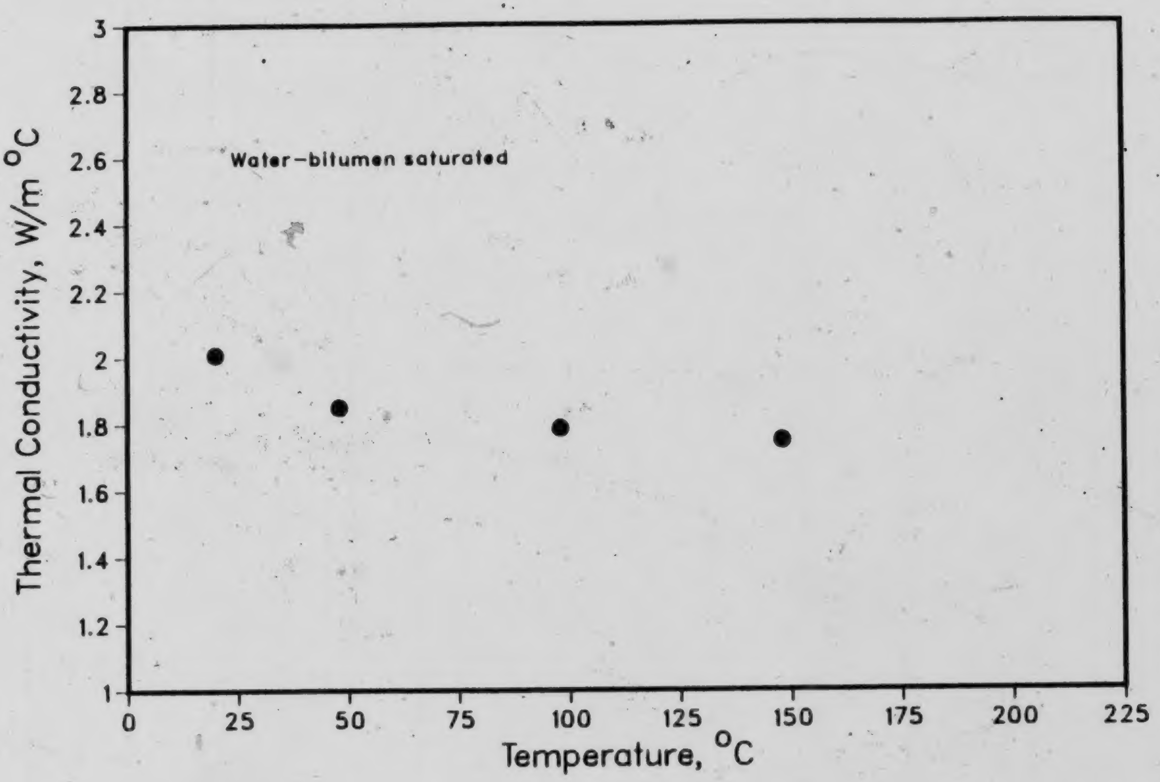


Figure 5.11 Change in Thermal Conductivity with Temperature, Medium Undisturbed Oil Sand

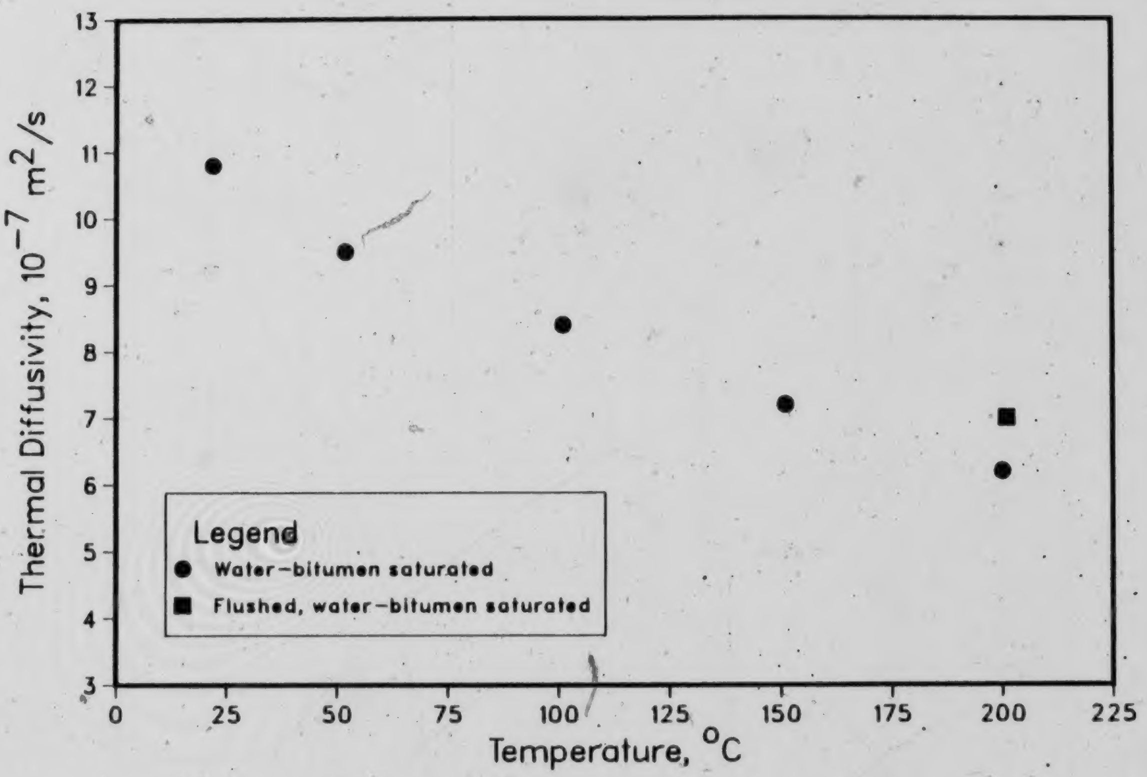


Figure 5.12 Change in Thermal Diffusivity with Temperature, Medium Undisturbed Oil Sand

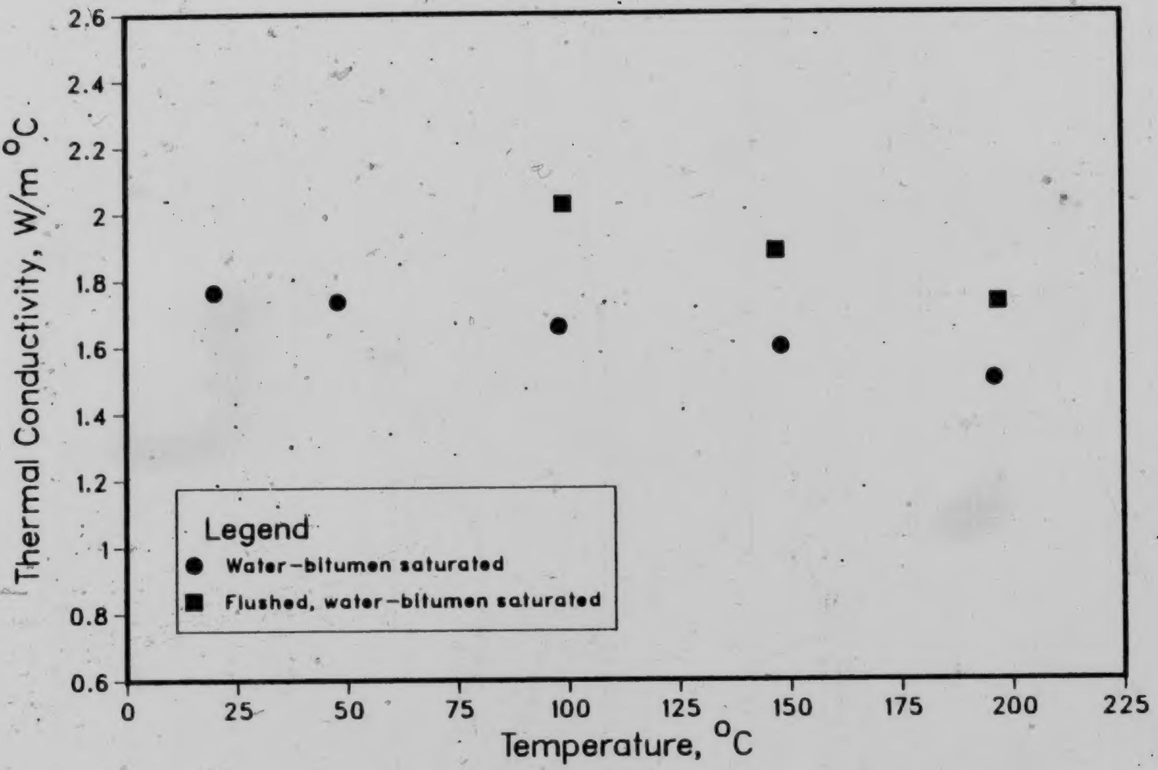


Figure 5.13 Change in Thermal Conductivity with Temperature, Rich Undisturbed Oil Sand

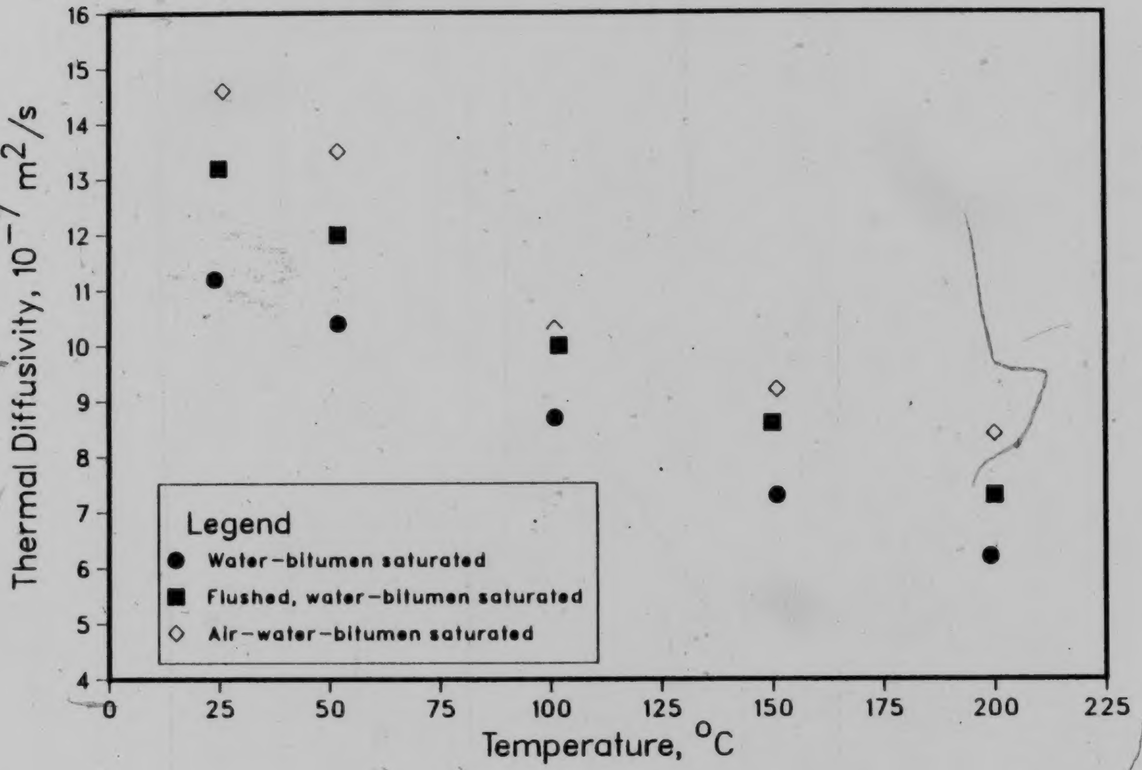


Figure 5.14 Change in Thermal Diffusivity with Temperature, Rich Undisturbed Oil Sand

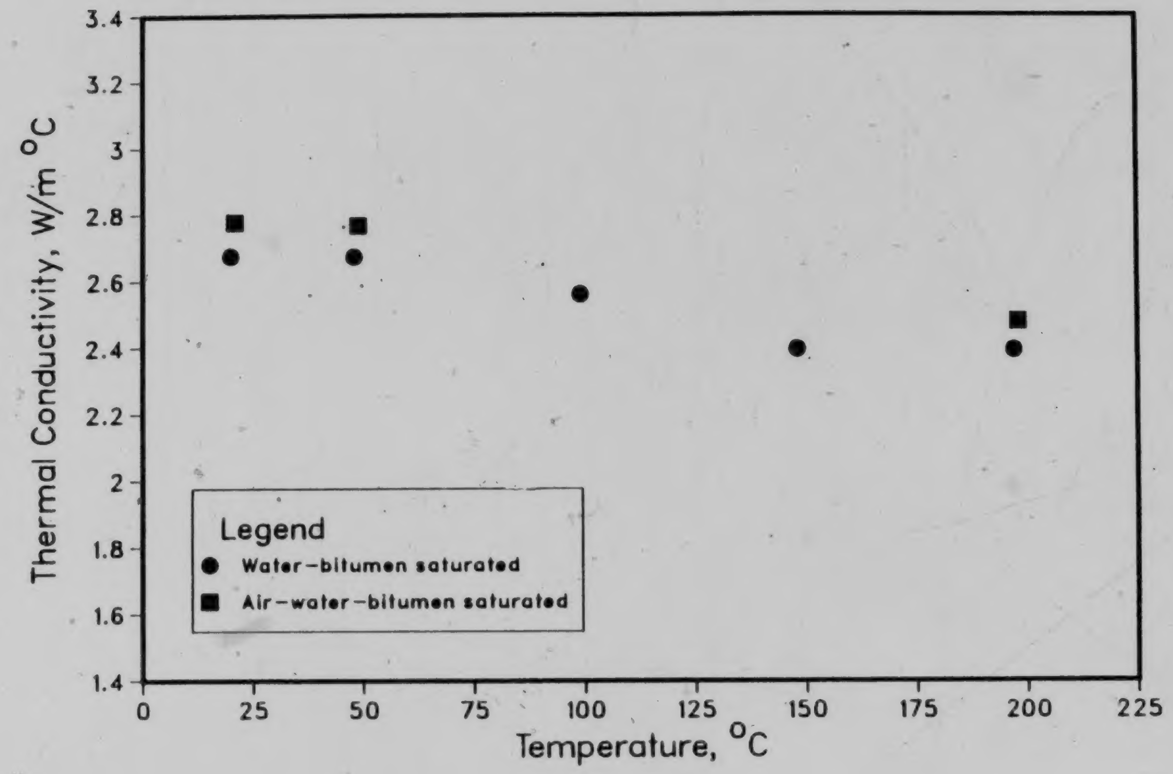


Figure 5.15 Change in Thermal Conductivity with Temperature, Lean Undisturbed Oil Sand

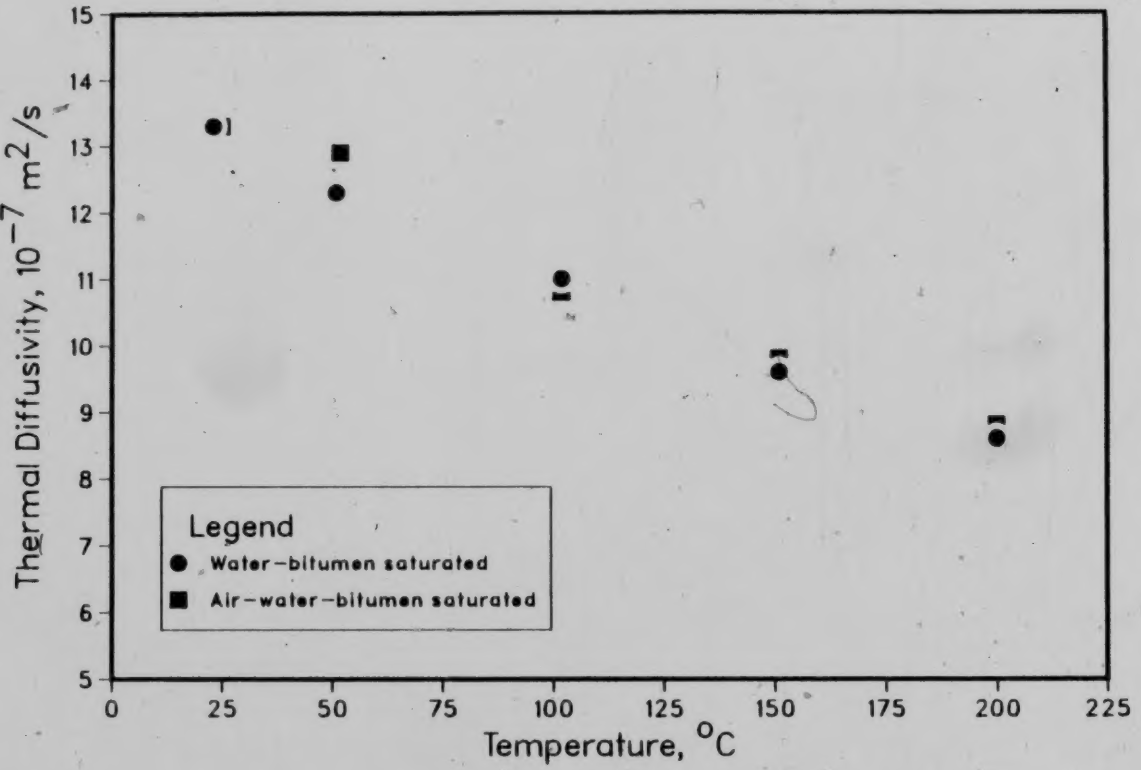


Figure 5.16 Change in Thermal diffusivity with Temperature, Lean Undisturbed Oil Sand

6. DISCUSSIONS OF LABORATORY TEST RESULTS

6.1 Sensitivity of Thermal Conductivity to Power Input

Figure 5.2 depicts the sensitivity of measured thermal conductivity values to varying voltage (thus power) inputs. At higher voltage inputs, the average sample temperature is higher for the same period of testing. Therefore, the increase in measured thermal conductivity of the dry quartz sand from 0.42 to 0.56 W/m °C with increasing power input may be partially attributed to the increase in mean temperature. The effects of varying power inputs on thermal conductivity measurements of the saturated sand, 3.40 W/m °C (±6 %), are not as prominent. The presence of water as a major heat absorbing element in the sample may have a stabilizing effect on the susceptibility of the sample to varying magnitudes of the power supply.

To minimize the increase in average sample temperature and the thermal gradients across the thermal conductivity probe surface, the magnitude of the power source should be kept low. Since the J-type (iron-constantan) thermocouples used in this study have a ±0.1 °C accuracy, temperature measurements would have to be relatively high enough to minimize instrument errors. It was found that a voltage input of 20 V would give a maximum temperature rise of about 10 °C during a thermal conductivity test. This represents approximately 1 % error in temperature measurements. The power supply unit was thus set at a constant voltage of 20 V for all thermal conductivity measurements. As shown in Figure 5.2, reproducibility of test results was found to be within 4 % for the water-saturated quartz sand with this voltage input.

6.2 Steady State Versus Transient State Testing of Quartz Sand

6.2.1 Thermal Conductivity

Results of steady state and transient state thermal conductivity measurements on dry and water-saturated quartz sand samples at room temperatures are compared as shown below:

	DRY SAND			WATER-SATURATED SAND		
	ρ g/cm³	n %	k W/m °C	ρ g/cm³	n %	k W/m °C
Steady state	1.800	32.0	0.43	2.134	32.0	4.03
Transient state (20 V input)	1.787	32.6	0.44	2.113	32.6	3.41

The densities of the specimens are close enough for a good comparison of the results. Thermal conductivity values of the dry Ottawa sand samples are quite compatible. The higher measured conductivity of water-saturated sand under steady state testing condition may be attributed to moisture redistribution and convective effects in this type of test. This further strengthens the point made previously that steady state hot plate tests should be used strictly for dry specimens only. The compatibility of measured thermal conductivity values of the dry Ottawa sand specimens suggests that reasonable accuracy may be obtained from transient state testing using the thermal test cell designed for this research.

As also noted by Combs, Quiett and Axtell (1977), thermal conductivities of moist materials measured using a needle-probe (thermal conductivity probe) method are often less than those obtained using a steady state method. They attribute the higher steady state thermal conductivity values to the effects of convective heat transfer in the water fraction of the aggregates. Hutcheon and Paxton (1952) have studied the effects of moisture migration in a closed guarded hot plate. The authors concluded that the thermal conductivity values obtained by testing moist materials in a hot plate may be of limited value when used in the usual heat flow equations for prediction of heat transmission. Since the transient state thermal test cell is devised to minimize convective effects during a thermal conductivity test, results obtained by using the apparatus may be more applicable to actual field conditions.

6.2.2 Thermal Resistance in Steady State Tests

As indicated by the non-zero dT/dq_s-axis intercepts in Figure 5.1, the effects of thermal contact resistance on steady state thermal conductivity testing are not negligible. The apparent thermal conductivity calculated from a hot plate test on a particular specimen should be smaller than its actual conductivity because of thermal contact resistance between plate surfaces. The difference between apparent (Table 5.1) and actual thermal conductivities (Figure 5.1) of the dry sand sample is less than 7 %. However, apparent thermal conductivity (Table 5.2) of the water-saturated quartz sand is about 24 % less than the corrected value (Figure 5.1).

Since thermal conductivity of water is higher than that of air, one would anticipate that thermal contact resistance across a film of water is a lot less than that across an air gap and would be negligible for steady state hot plate testing on water-saturated samples. The higher thermal resistance (0.20×10^{-2} m^2 °C/W) measured from the hot plate test on the wet sand therefore suggests that there may be an additional impedence or power loss to the system other than thermal contact resistance. It is speculated that the extra thermal resistance is generated by convective currents flowing inside the water-saturated specimen. Part of the constant power supply may be consumed as energy for the convection process. The steady state heat conduction equation (3.5) for a hot plate apparatus may thus be too simple to be used to describe this complex problem of heat and fluid transfer. One simple way of interpreting the thermal conductivity value measured for the water-saturated sand is to treat the value as an apparent thermal conductivity influenced by convective effects.

6.3 Calculated Versus Experimental Thermal Diffusivity Results

Thermal diffusivity values calculated from thermal conductivity tests (Section 3.3.2.2) are plotted against experimentally established values as shown in Figure 6.1. It appears that the calculated values are generally smaller than the experimental ones. This can easily be explained by the fact that the point of internal sample temperature measurement is assumed to be right at the thermal conductivity probe wall (at r = 1/16 in). If the exact radial distance of the internal thermocouple tip (at r = 3/32 in) were used in the expression for coefficient B of equation 3.13, the calculated diffusivity values would have been increased by a factor of 2.25 (square of the ratio of the two radii). However, as discussed in Chapter 3, Hooper and Chang (1953) state that the apparent radial distance of the temperature measurement point changes with different test materials. Hence, no attempt was made to re-adjust the original assumed radius. As mentioned earlier, the calculated thermal diffusivity values should be taken as accurate for the order of magnitude only. Thermal diffusivity tests therefore must be performed to obtain accurate results.

As demonstrated above, the major source of error in calculating thermal diffusivity values from thermal conductivity tests is the uncertainty in locating the apparent point of temperature measurement. The other error in thermal diffusivity calculation is from the assumption of negligible thermal contact resistance. This assumption holds for testing of fully saturated materials near room temperature condition. The error may be large during thermal testing of dry materials at elevated temperatures.

6.4 Evaluation of Experimental Procedures by Specific Heat Calculation

6.4.1 Comparison of Experimental and Calculated Specific Heats

The simple relationship among the thermal properties and the density of a material (equation 3.7) provides a good means to evaluate the experimental procedures followed in this research. Specific heats may be estimated from experimentally established values of thermal conductivity, thermal diffusivity and density. Since it is well documented that the weighted average method for calculating specific heats is fairly accurate, a comparison of the experimental specific heats with the calculated values using this method should give a good indication to the adequacy of the experimental procedures.

Figure 6.2 displays a comparison of experimental specific heat values with those calculated using the weighted average method. It is observed that the maximum deviation of the experimental results from the calculated values is about 20 % while most of the deviations fall within 15 %. Assuming a maximum error of 5 % in specific heat approximation using the weighted average method, 5 % in thermal conductivity measurement and 5 % in density estimation, much of the 15 % error in specific heat evaluation may be accounted for.

Considering the fact that the comparison is made based on specific heat calculations involving the many different parameters that are subject to errors, the average deviation of only about 15 % is quite acceptable. The experimental set-up, the thermal conductivity and thermal diffusivity equations and the testing procedures are thus proven to be highly adequate for thermal testing.

6.4.2 Thermal Diffusivity Measurements

In addition to depicting the proximity of the experimental and the calculated specific heats, Figure 6.2 also displays a consistency in that the experimental specific heat values are lower than the calculated ones in most instances. This consistent discrepancy in specific heat values deserves further investigation.

As may be noted from the discussion above, the error in thermal diffusivity measurement has not been considered. It is suspected that this contributes as the major source of consistent error in specific heat approximation. A plot of the ratio of experimental to calculated specific heat values against degree of water saturation is depicted in Figure 6.3. It can be observed that most of the ratios fall between 0.8 to 0.9 except for those of the dry quartz sand sample (QS, at 0 % water saturation) that are very close to 1.0. All other samples are either partially or fully saturated. It appears that the introduction of water into the pore space of a specimen incurs a certain degree of complexity in the heat transfer mechanism during thermal testing. Instead of heat transfer by pure conduction alone, whereby the thermal conductivity and diffusivity equations were derived (Chapter 3), convection of fluids and/or vaporization and condensation of moisture also play certain roles in heat transmission within the moist medium. Such effects on thermal conductivity measurements should be small because the central axis of the specimen is heated by the probe heater for a very short period of time. Moreover, heat is dissipated from a very small area in the middle to the larger area at the exterior of the sample. The amount of energy supplied should be insufficient to induce high pore pressures such that convective effects become dominant. On the other hand, heating of the sample surface by the external jacket heater during a thermal diffusivity test may generate enough pore pressure at this larger circumferential area that moisture migration or convection may take place towards the centre of the specimen. Compounded by this moisture/fluid migration mechanism, heat transfer from the exterior to the interior of the wet specimen may appear to be faster, thus rendering a higher measured thermal diffusivity value. Therefore, the specific heat of a moist material calculated using this measured thermal diffusivity value (equation 3.7) appears to be smaller than the actual number.

Assuming that measurements of thermal conductivity and calculations of density and specific heat (using the weighted average method) are fairly accurate, Figure 6.3 thus depicts the experimental errors in thermal diffusivity measurements. A correction factor, say 0.85 to 0.90, may be applied to an experimentally established thermal diffusivity value of a moist sample to obtain the true or corrected value.

It is believed that a small forced convection or moisture migration mechanism does exist during a transient state thermal diffusivity test on a moist material using the present apparatus. However, the laboratory apparatus, the theories and the thermal testing procedures used in this research have been proven to be very adequate as an error of only 10 % to 15 % is shown by the specific heat results.

6.5 Factors Affecting Thermal Properties of Oil Sands

The scope of the current study, as outlined earlier, covers mainly the development of the transient state thermal test cell as well as the theories that support it. The thermal testing program is designed to furnish some information on the thermal properties of Athabasca oil sands. In addition, a few of the factors that affect such properties (Table 1.1) are also investigated. Based on the experimental results presented in Chapter 5, the following observations are made:

Temperature

The effects of temperature on the thermal properties of fluid saturated oil sands have been studied rather extensively in this study. Thermal diffusivity is found to decrease with increasing temperature. The decrease in diffusivity, for a temperature increase from 20 °C to 200 °C, ranges from about 14 % for the partially saturated lean remoulded oil sand to about 45 % for the water-bitumen saturated rich undisturbed oil sand. It appears that the higher the bitumen saturation of a specimen, the greater the percent drop of diffusivity value with increasing temperature.

Although Seki, Cheng and Fukusako (1981) noted a slight rise in thermal diffusivity of their oil sand sample from about 20 °C to 80 °C, a general trend of decreasing thermal diffusivity with increasing temperature can be observed from Figure 2.3. Since their test data were affected by vaporization of fluids at high temperatures, it is believed that the thermal diffusivity values obtained from this research are more representative of the *in situ* oil sand deposits.

With the exception of the partially saturated lean remoulded oil sand specimen, all measured thermal conductivity values of oil sand samples were found to decrease with increasing temperature. The percent drop ranges from about 11 % for the lean undisturbed sample to about 28 % for the rich remoulded sample from 20 °C to 200 °C. Again, a higher decrease is marked by the rich oil sand samples with higher bitumen saturations. The increase in thermal conductivity of the lean remoulded oil sand specimen with temperature may be attributed to a density increase which took place due to load consolidation as well as heat consolidation during thermal testing.

The drop in thermal conductivity of oil sands with increasing temperature has also been observed by many investigators. Thermal conductivity of the 18%-bitumen Athabasca oil sand specimen obtained by Karim and Hanafi (1981) decreases by about 25 % from 20 °C to 120 °C (Figure 2.1). Somerton's (1973) Kern River oil sand specimen (with 38 % oil saturation, 61 % total liquid saturation) exhibits a reduction in thermal conductivity of about 10 % for a temperature increase from 20 °C to 120 °C. The general trend of decreasing thermal conductivity with increasing temperature is also depicted in Figure 2.3 by Seki, Cheng and Fukusako (1981). Thermal conductivity of oil shales is also found to decrease with temperature increase as shown in Figure 2.7 by DuBow *et al* (1978). This comparison is made because of the similarity of oil shales and oil sands in that they both contain oil/bitumen and water as saturants.

Temperature dependence of the thermal conductivity of dry quartz sand shows an opposite trend (Figure 5.3). Thermal conductivity increases from 0.51 to 0.55 W/m °C for a temperature increase from 20 °C to 200 °C. The density of the quartz sand sample is 1.74 g/cm^3. The same trend has also been noted by other researchers. Flynn and Watson (1969) showed an increase in the average thermal conductivity of their dry Ottawa sand sample (with density of 1.76 g/cm^3) from 0.37 to 0.44 W/m °C for a temperature rise from 25 °C to 200 °C.

Bitumen/Water Proportions

Figures 6.4 and 6.5 display the changes in thermal conductivity and thermal diffusivity with bitumen saturation respectively. The data plotted represent oil sand specimens that are 100 % saturated by water and bitumen. Therefore, the dependence of the thermal properties on water saturation may be visualized by simply reversing the horizontal axis from 100 % to 0 %.

As depicted in Figure 6.4, thermal conductivity of a fully saturated sample decreases with increasing bitumen saturation (or decreasing water saturation). Thermal conductivity values of undisturbed oil sand specimens are higher than those of the remoulded ones at roughly the same bitumen saturation. It is believed that higher densities of the undisturbed specimens attribute to the difference. Thermal conductivity values of the oil sand specimens appear to drop quite drastically for a bitumen saturation change from 0 % to near 20 %. The reduction is about 60 %. The decrease in thermal conductivity then tapers off at higher bitumen saturations.

Clark (1944) (Table 2.1) and Karim and Hanafi (1981) (Figure 2.1) indicate that an increase in bitumen content increases the thermal conductivity of oil sands. Somerton, Keese and Chu (1974) and Cervenan, Vermeulen and Chute (1981) (Table 2.5) show that, for the same degree of saturation, an increase in bitumen content decreases the thermal conductivity. From the observations made from thermal conductivity tests on the oil sand samples of varying bitumen/water proportions used in this study, it is found that the latter trend is correct. The decrease in thermal conductivity of oil shales with increasing oil grade (thus hydrocarbon content), as shown in Figure 2.7, also supports this view. The lack of control on the pore water contents in many of test procedures causes the difference in test results obtained by other investigators. If little or no water is present in a sample, the increase in bitumen content may actually increase the thermal conductivity. However, samples in this state would generally not be reflecting *in situ* conditions during a thermal stimulation process.

Thermal diffusivity of saturated oil sand is shown to decrease with increasing bitumen saturation in Figure 6.5. However, more significant differences between thermal diffusivity values of undisturbed and remoulded oil sand specimens at roughly the same bitumen saturation are observed. This indicates that thermal diffusivity is affected to a much greater degree by density difference than thermal conductivity is. It can also be observed that the decrease in thermal diffusivity of undisturbed samples with increasing bitumen saturation is rather gradual. A sharp drop of thermal diffusivity (30 % to 70 %) is observed for remoulded oil sand specimens with bitumen saturations increasing from 0 % to near 20 %. At higher bitumen saturations, the change in thermal diffusivity is less pronounced.

Degree of Saturation

The effects of degree of liquid saturation on thermal conductivity and thermal diffusivity of oil sands are shown graphically in Figures 6.6 and 6.7 respectively. Both thermal conductivity and thermal diffusivity of oil sands are shown to increase with degree of saturation. Variations from the general trends are probably due to differences in density and bitumen/water proportions. Again, significant influence of density on thermal diffusivity is observed in Figure 6.7. The undisturbed samples have higher thermal diffusivity values than those of the remoulded ones.

Density

As mentioned during the discussions on the previous factors, density (or porosity) has significant effects on the thermal properties of a material. The general trend of higher thermal conductivity and diffusivity values for the denser undisturbed samples can be visualized from Figures 6.4 and 6.5. The effects of density difference on changes in thermal diffusivity (about 21 to 53 %) are more pronounced than in thermal conductivity (about 15 to 18 %). Since it is impossible to recompact an oil sand structure back to its original 'locked' state, a remoulded oil sand specimen should have a higher porosity than that of the original sample. Therefore, in order to achieve more representative results that may be used in the field, undisturbed oil sand samples should be used for thermal property testing.

Mineral Grains and Soil Structure

Oil sand samples from two different localities of the Athabasca deposits were tested for the current study. Samples from the Syncrude site contain more silty materials than the ones from Saline Creek. A general comparison of the values listed in Tables 5.6 to 5.10 indicates that the lean oil sand specimens have higher thermal conductivity values than the rich ones under roughly the same conditions. The difference may be partially attributed to the slight difference in mineralogy. The major source of variations stems from the difference in soil structure. With more fines in the void space between the crystalline grains in the soil matrix, greater amount of contact areas are created for the better graded lean oil sands. Heat conduction through the specimen is facilitated by the provision of more conductive flow paths. On the other hand, the number of surface contacts is smaller for a poorly graded material. Assuming that degree of saturation and fluid saturant proportions are the same, the poorly graded material (Saline Creek oil sand) should exhibit lower thermal conductivity.

The same comparison is made for thermal diffusivity. The effects of mineralogy and soil structure are less prominent.

6.6 Comparison of Thermal Conductivity Results with Published Data

6.6.1 Quartz Sand

Thermal conductivity values of quartz sand and extracted oil sand samples obtained by the various researchers mentioned in Chapter 2 are tabulated in Table 6.1. The results obtained from this study are also included.

It can be observed that thermal conductivity values (0.44 and 0.49 W/m °C) of the dry quartz sand and tailings quartz sand specimens measured by the transient state thermal test cell are quite comparable to the published data. Thermal conductivities of the water-saturated samples (3.88 and 3.41 W/m °C) appear to be on the high side of the range of published values. The differences would be due to differences in mineralogy, grain size distribution and density.

6.6.2 Oil Sands

Figure 6.8 displays a comparison of the thermal conductivity values of Athabasca oil sands determined by different investigators (Chapter 2). The results reported by Somerton, Keese and Chu (1974) are not included in the figure because of the difference in mineralogy and grain size distribution. Thermal conductivity values of the saturated medium undisturbed oil sand specimen (with 12 % bitumen by mass) are also plotted for comparison.

It is of interest to note from Figure 6.8 that none of the published data fall above the line represented by the medium grade oil sand. As discussed earlier, the higher the hydrocarbon content (or saturation) of a water-bitumen saturated material, the lower its thermal conductivity. Therefore, it is anticipated that at least some of the published data for water-bitumen saturated, but leaner (lower bitumen saturation), oil sand samples would show higher thermal conductivities than those of the medium undisturbed oil sand. The main reason for this prediction not being realized is that the densities of the reconstituted or remoulded oil sand specimens tested by other researchers are generally lower than that of the undisturbed specimen used in this study. The relative intact soil structure of an undisturbed oil sand sample provides better contacts for heat conduction than the disrupted structure of a remoulded sample. The inability to provide sufficient back pore fluid pressure to maintain gases in solution at high temperatures also accounts for some of the variations of results. The medium oil sand specimen was fully saturated while some of the other specimens prepared by the other researchers were only partially saturated. The difference in the degrees of saturation also attributes to the difference in the thermal conductivities.

Variations in thermal conductivity of the water-saturated and dry quartz sand samples with temperature are also delineated in Figure 6.8 because they represent the upper and lower boundaries respectively of the thermal conductivity of Athabasca oil sands. Since bitumen has a lower thermal conductivity than water and higher than air (Appendix A), all oil sands with different air-water-bitumen saturations will exhibit thermal conductivities between these boundaries. However, as the upper values are seven to five times the lower values, the boundaries may not be taken as a guide to assist the determination of thermal conductivity. Nevertheless, the significant effect of air-water-bitumen saturation on thermal conductivity is illustrated by the plots.

The thermal conductivity data of the fully liquid saturated undisturbed oil sand samples are plotted in Figure 6.9. The upper and lower boundaries are also included in the figure. In keeping with the findings covered earlier, oil sand specimens with high bitumen contents have lower thermal conductivities. The leaner or the lower the bitumen content of a fully saturated sample, the closer its thermal conductivity is to the upper boundary.

Figure 6.10 displays a similar comparison of the thermal diffusivities of the fully liquid saturated undisturbed oil sand samples. Calculated diffusivities from Seki, Cheng and Fukusako (1981) are also included. As observed previously, the higher the bitumen proportion of a water-bitumen saturated oil sand sample, the lower its thermal diffusivity. The importance of undisturbed sample testing is again demonstrated as the less dense disturbed oil sand specimen (9 % bitumen) prepared by Seki, Cheng and Fukusako (1981) exhibits much lower thermal diffusivities than anticipated. Vaporization of fluids at about 100 °C also significantly complicated the thermal conduction process. The provision of a back pore fluid pressure system to their thermal testing apparatus would have avoided this problem.

Table 6.1 Comparison of Thermal Conductivities of Quartz Sand

Thermal Conductivity W/m °C	Porosity %	Density g/cm^3	Water Saturation %	Reference & Remark
0.41	34	1.76	0.0	Kersten (1949); At 100°C; 20-30 Ottawa sand.
0.627	-	-	0.0	Somerton (1958); Fine sand.
2.752	-	-	100.0	Fine sand
0.557	-	-	0.0	Coarse sand
3.072	-	-	100.0	Coarse sand
0.257-0.314	37-41	-	0.0	Krupiczka (1967)
0.38	-	1.76	0.0	Flynn and Watson (1969);
0.26	-	1.57	0.0	20-30 Ottawa sand.
0.254-0.575	30-50	-	0.0	Somerton, Keese and Chu (1974)
1.419-3.756	30-50	-	100.0	Brine saturated
2.684±0.032	-	-	-	Poulsen et al (1981)
0.337-0.466	31-45	-	0.0	Somerton, Keese and Chu (1974);
2.080-2.460	28-37	-	100.0	Extracted oil sands.
0.80	45	-	3.3	Cervenan, Vermeulen and Chute
1.24	45	-	12.7	(1981); Extracted oil sands;
2.39	43	-	62.2	Water saturations given by % total mass.
0.44	33	1.787	0.0	This study; 20-30 Ottawa sand.
3.41	33	2.113	100.0	20-30 Ottawa sand
0.49	35	1.700	0.0	Oil sand tailings sand
3.38	35	2.059	100.0	Oil sand tailings sand

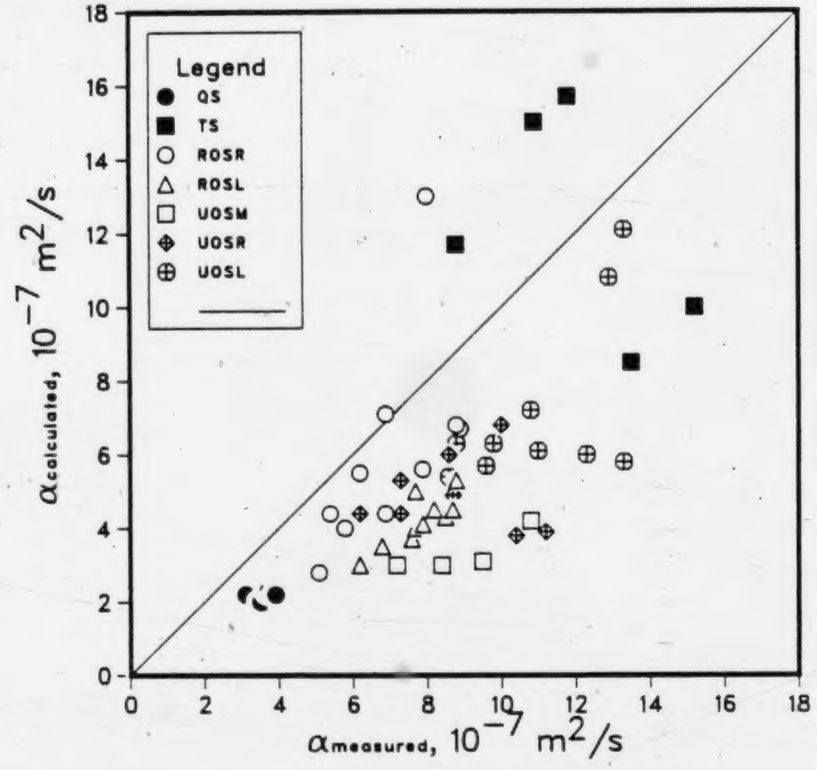


Figure 6.1 Calculated Diffusivity versus Measured Diffusivity

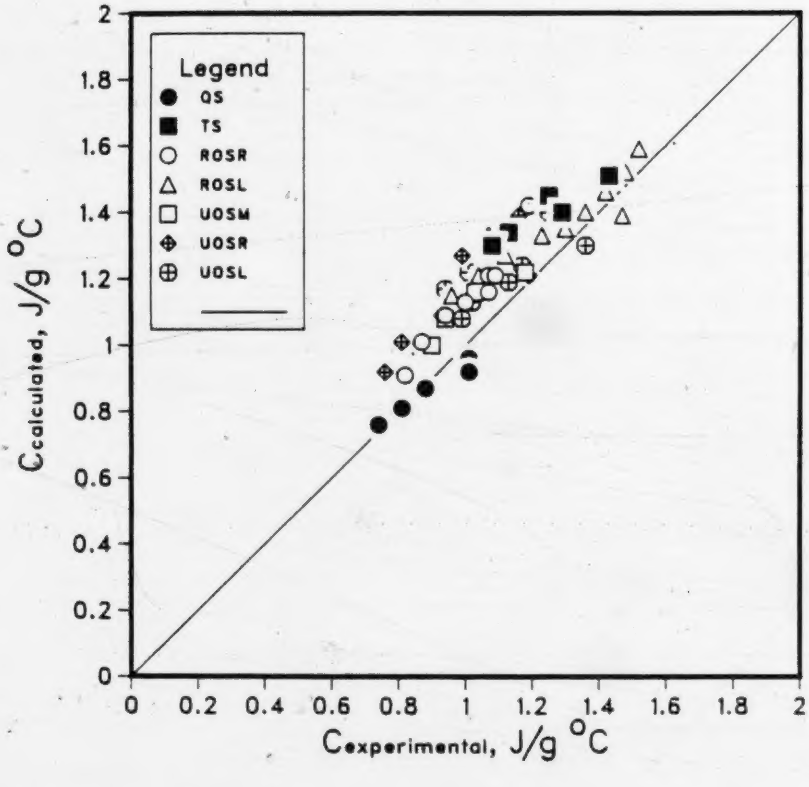


Figure 6.2 Calculated Specific Heat versus Experimental Specific Heat

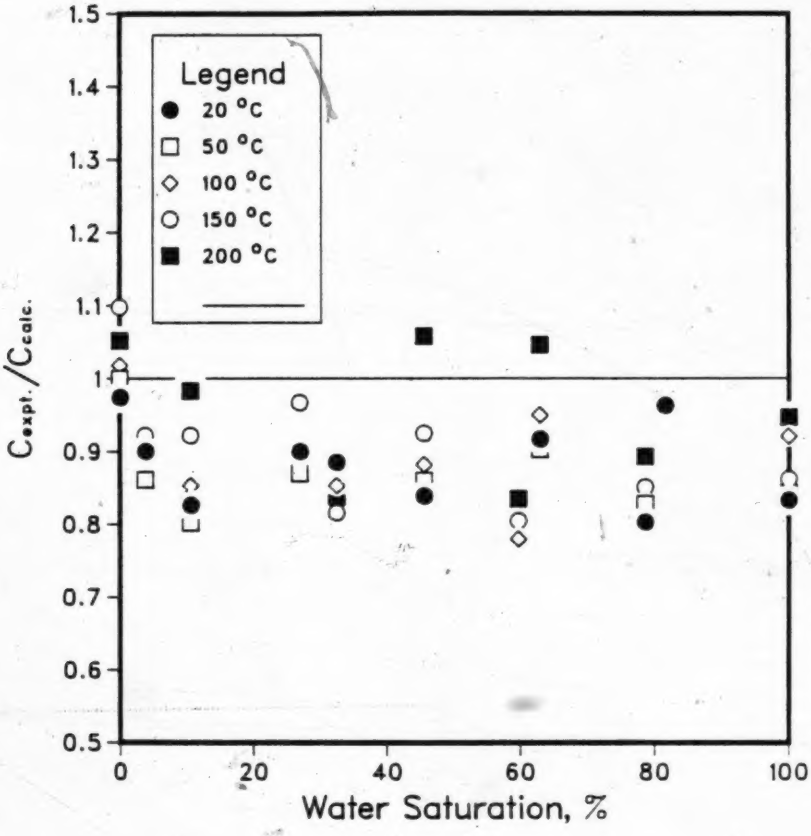


Figure 6.3 Experimental Error in Specific Heat Estimation

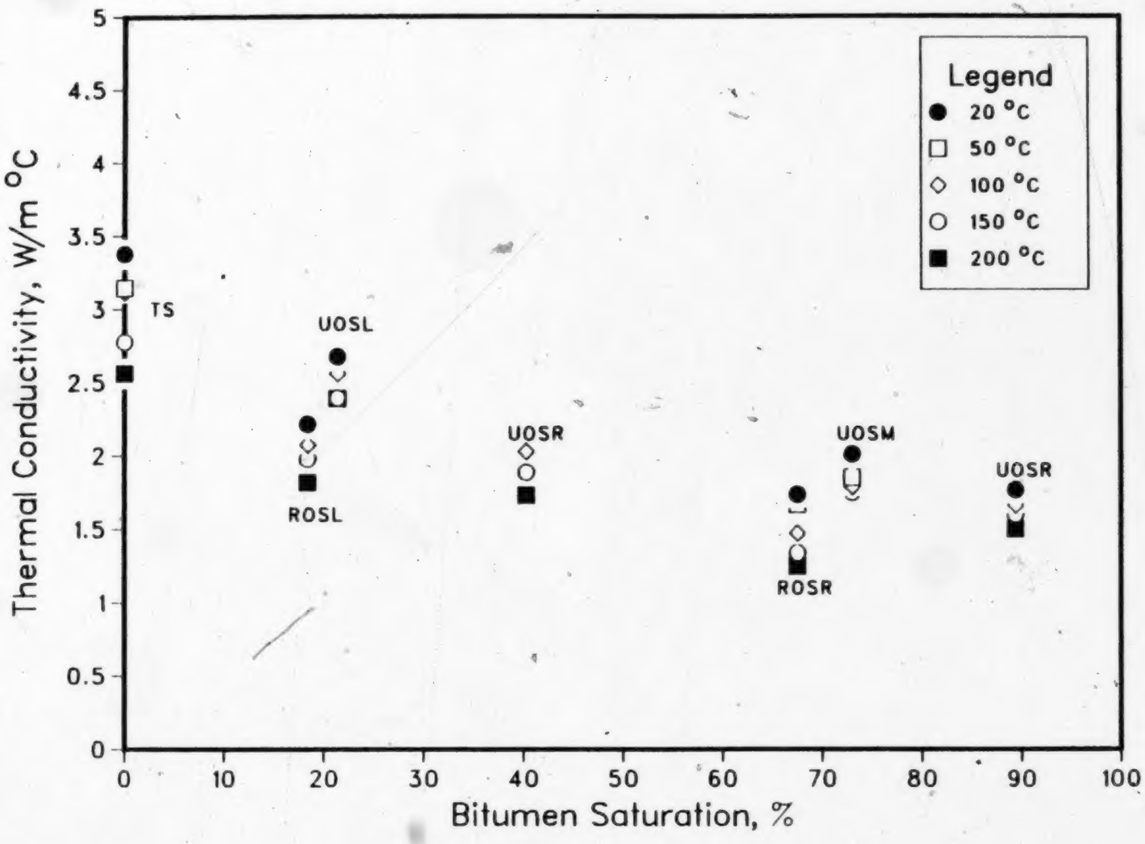


Figure 6.4 Change in Thermal Conductivity with Bitumen Saturation, Saturated Oil Sand

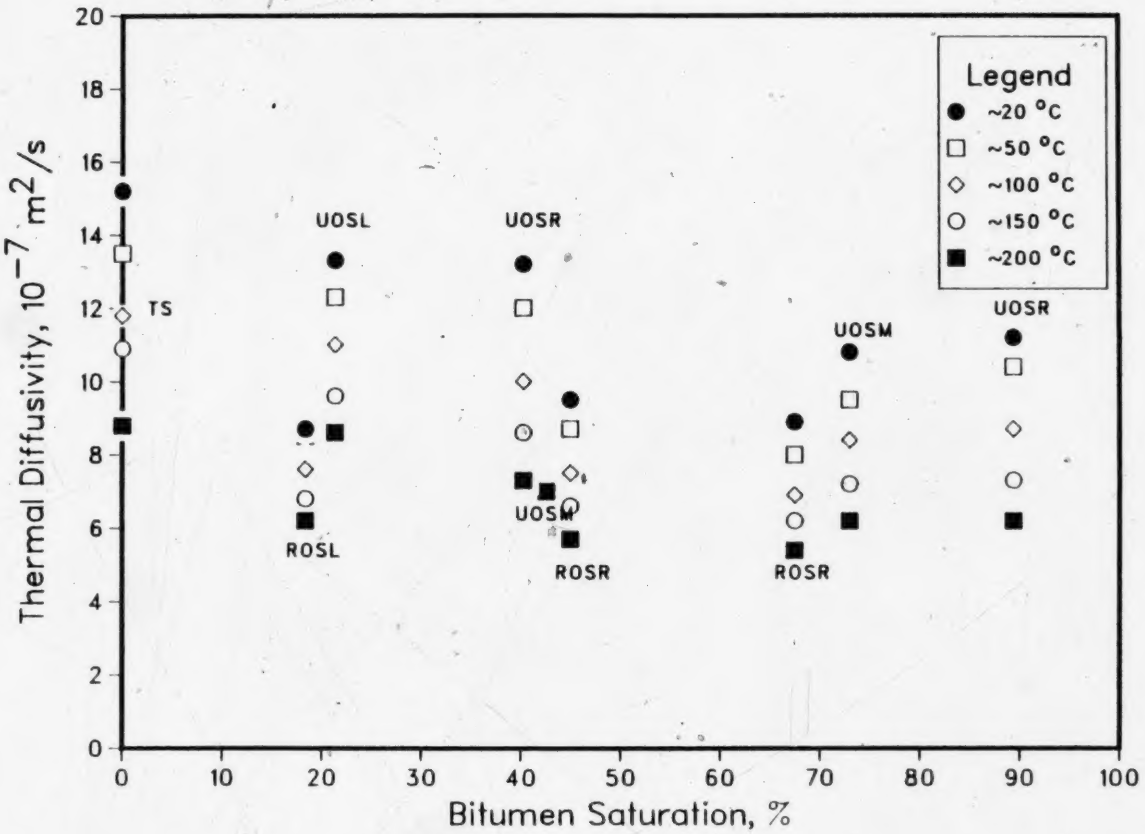


Figure 6.5 Change in Thermal Diffusivity with Bitumen Saturation, Saturated Oil Sand

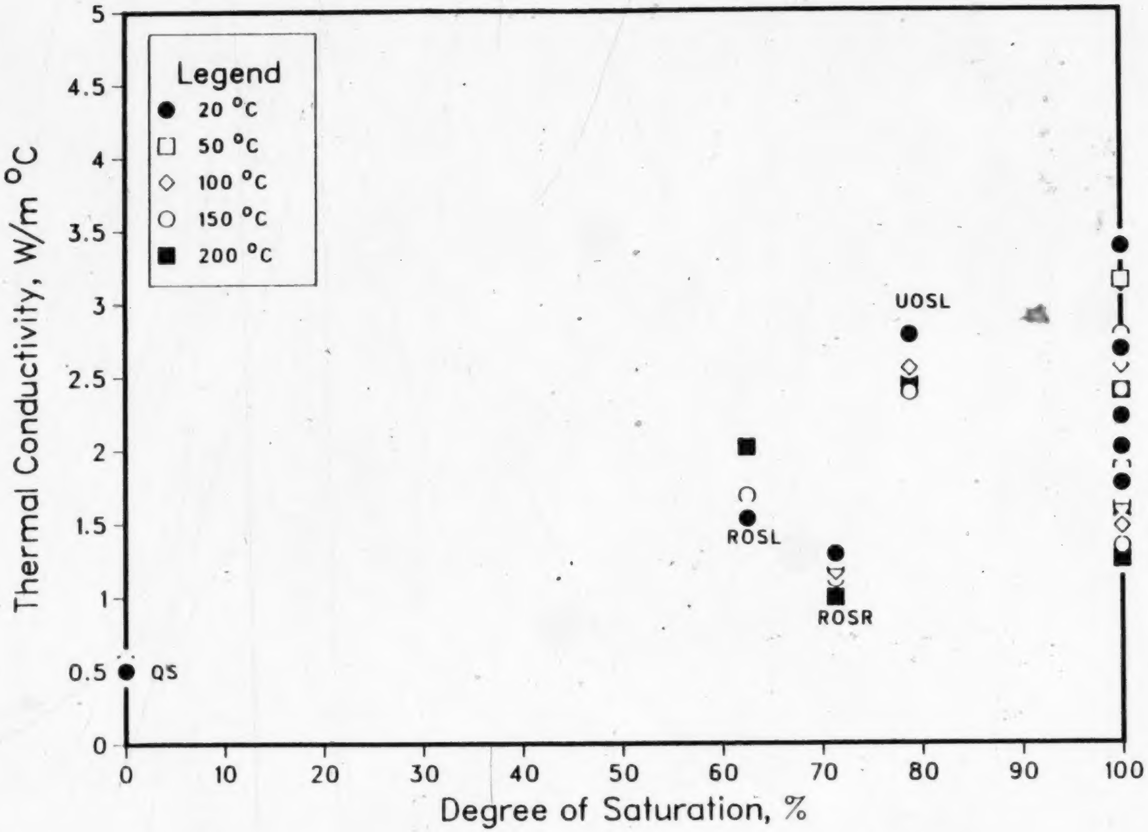


Figure 6.6 Change in Thermal Conductivity with Degree of Saturation, Oil Sand

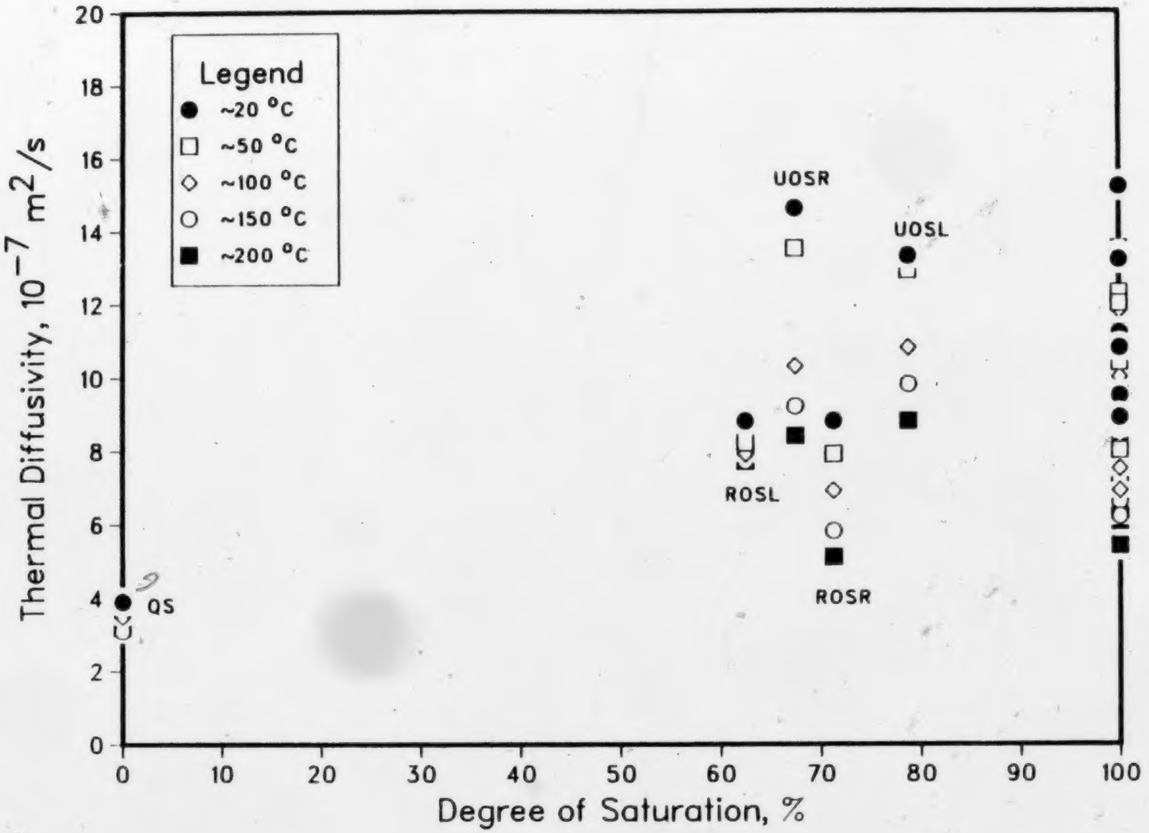


Figure 6.7 Change in Thermal Diffusivity with Degree of Saturation, Oil Sand

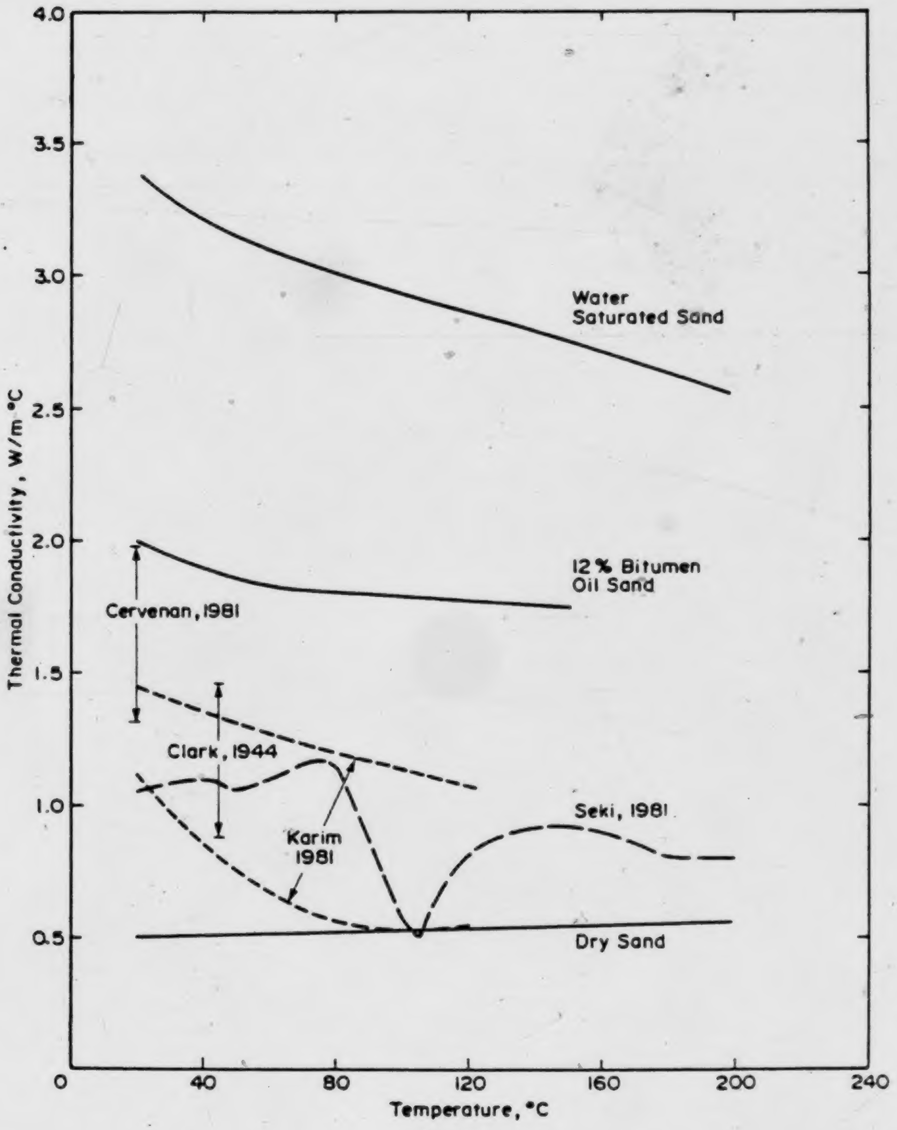


Figure 6.8 Comparison of Thermal Conductivity of Medium Athabasca Oil Sand Sample with Published Data

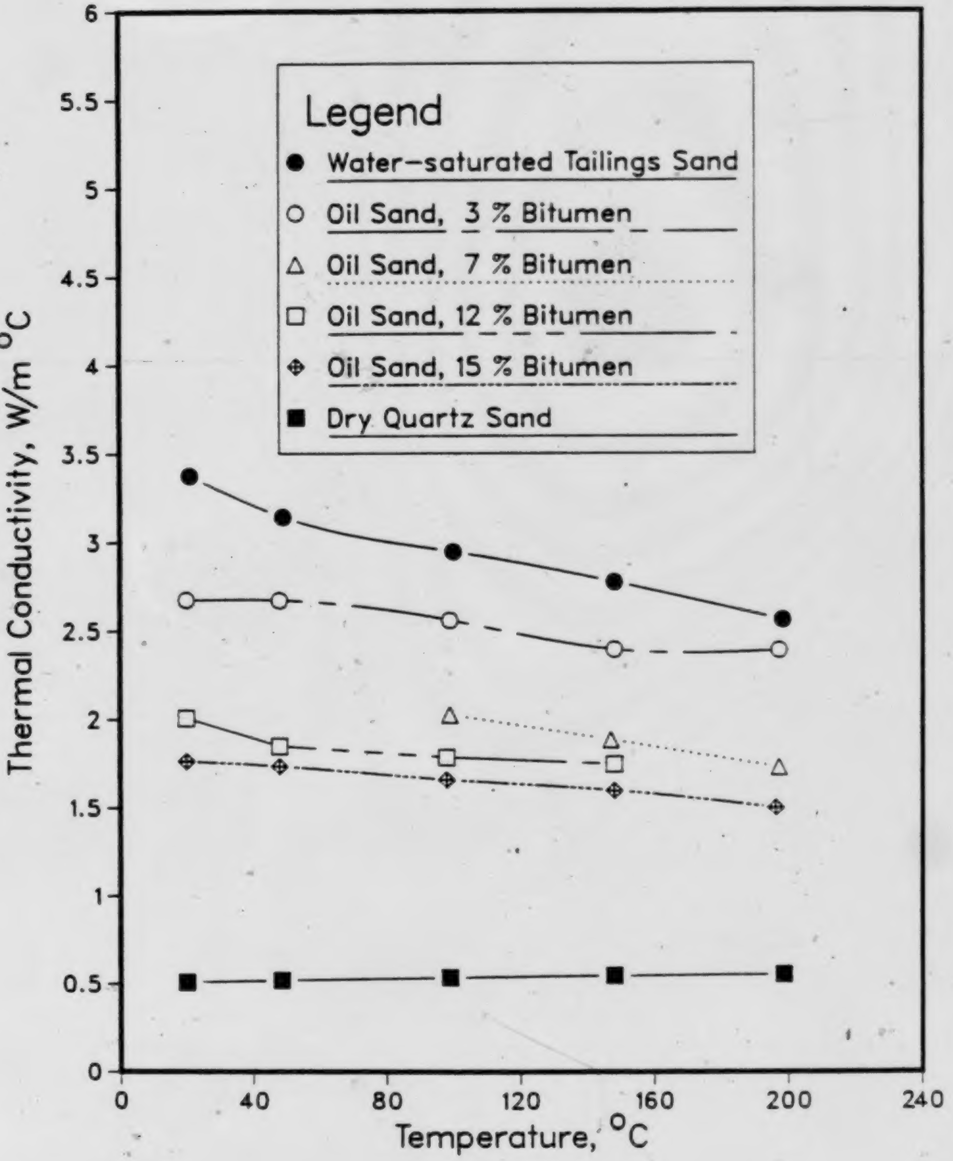


Figure 6.9 Comparison of Thermal Conductivities of Saturated Athabasca Oil Sand Samples

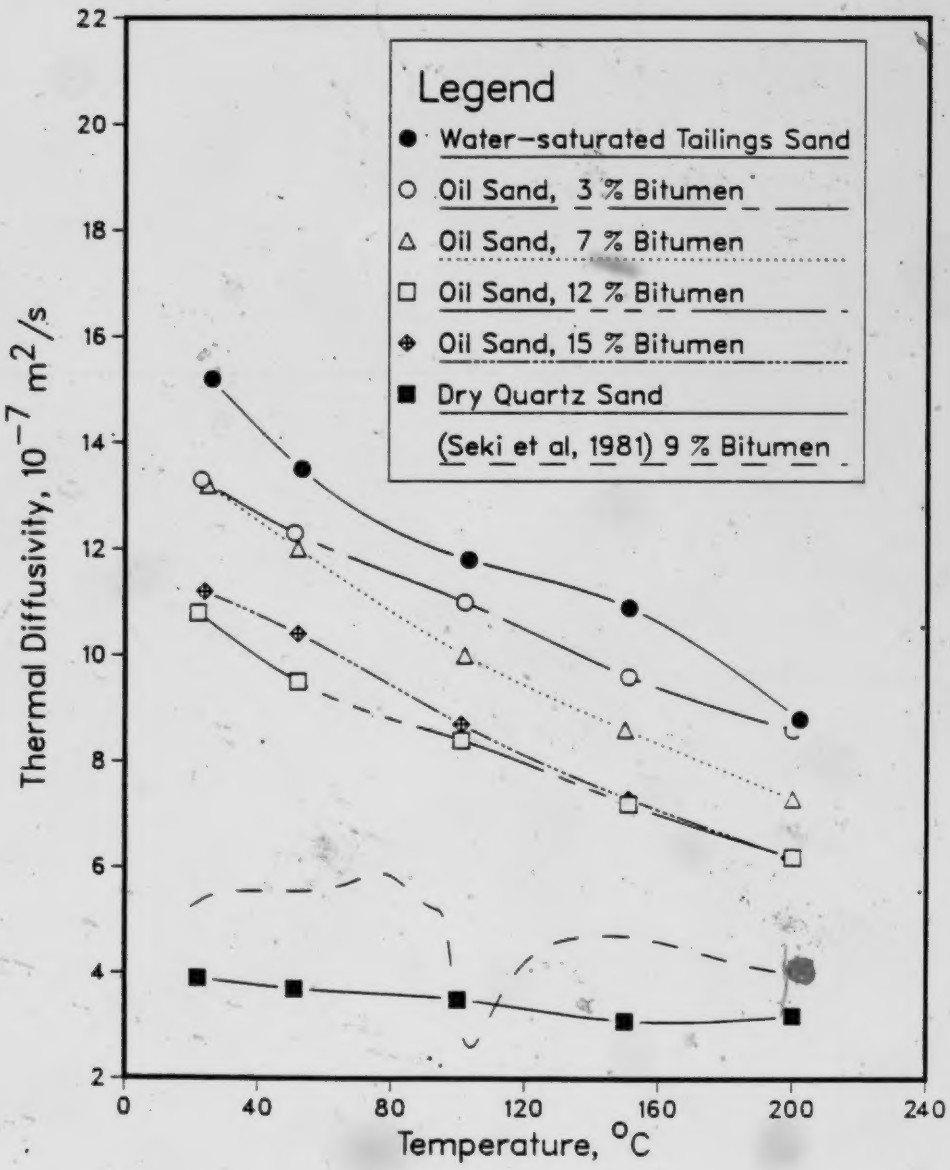


Figure 6.10 Comparison of Thermal Diffusivities of Saturated Athabasca Oil Sand Samples

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 General

During the course of this research, a great deal of time has been spent on developing the transient state thermal testing apparatus. Many modifications were made to enhance the capabilities of the thermal test cell for thermal testing of undisturbed oil sand specimens under simulated *in situ* pressure and temperature conditions. Based on the one-dimensional radial heat conduction theory, thermal conductivity and diffusivity equations that support the thermal testing apparatus were derived.

The latter part of the research was centred on thermal property determinations of quartz sand and oil sand samples. In addition to providing more information on the thermal properties of the Athabasca oil sand deposits, the testing program was designed such that several of the major factors affecting such properties were also investigated.

The relatively wide spectrum of the areas covered by this research has shed some light on the problem of thermal property determination, both experimentally and analytically. Conclusions drawn from major observations and findings are outlined below. Recommendations for further study and improvements are also included.

7.2 Conclusions

7.2.1 Experimental Apparatus and Procedures

The objectives of this thesis in developing an experimental apparatus as well as the appropriate testing and analytical procedures for measuring thermal properties of undisturbed oil sand core samples under simulated *in situ* conditions have been achieved. Based on the comparison with other published data and specific heat calculations, it appears that the values of thermal conductivity are measured with a very small error and those of thermal diffusivity with an error of only 10 % to 15 %.

7.2.2 Transient State Testing

As discussed rather extensively in Chapter 3, a transient state method of thermal testing on moist or water-saturated specimens is more favorable than a steady state approach. Together with the provisions of a drainage system and simulated *in situ* pressure and temperature conditions, the transient state thermal test cell devised for the current research is believed to be capable of producing more representative results for field applications.

7.2.3 Experimental Results

Although a limited number of thermal tests were performed, several conclusions may be drawn based on the experimental results.

1. *Effect of Temperature*

All partially or fully saturated oil sand samples exhibit a decrease in thermal conductivity with increasing temperature. The decrease ranges from 11 % to 28 % from 20 °C to 200 °C. Thermal diffusivities of all specimens decrease with temperature (14 % to 45 %). The higher the bitumen content of the material, the greater the percent decrease in thermal conductivity and diffusivity with temperature. Thermal conductivity of dry quartz sand increases by about 10 % for a temperature rise from 20 °C to 200 °C.

2. *Effect of Bitumen Saturation*

Both the thermal conductivity and thermal diffusivity of a fully saturated oil sand specimen decrease with increasing bitumen (or decreasing water) saturation. The decrease is quite drastic (30 % to 70 %) for bitumen saturation change from 0 % to 20 %. At higher bitumen saturations, the decline is less pronounced.

3. *Effect of Saturation*

Both the thermal conductivity and thermal diffusivity of an oil sand specimen generally increase with increasing degree of liquid saturation. The thermal conductivities and thermal diffusivities of dry quartz sand and fully water-saturated quartz sand are the lower and upper limits respectively for quartz-dominant Athabasca oil sands. Thermal conductivities of water-saturated quartz sand are seven to five times those of dry quartz sand from 20 °C to 200 °C. Thermal diffusivities of the water-saturated sand are found to be about four to three times those of the dry sand for the same temperature range.

4. *Effect of Density*

Density (or porosity) has significant effects on the thermal properties of oil sands. The higher the density of the material, the higher its thermal property values. The effects are more prominent in thermal diffusivity than in thermal conductivity. The undisturbed oil sand samples exhibit higher values of thermal conductivity and thermal diffusivity than the less dense remoulded samples.

Considering the aforementioned factors that may significantly affect the thermal properties of oil sands, it is recommended that thermal property measurements be carried out on undisturbed core samples that are representative of the location of interest. Pressure, temperature and saturation conditions of the field should also be simulated as closely as possible for more representative thermal testing results.

7.3 Recommendations for Future Research

Recommended future research in the investigation of heat transmission properties of oil sands may be divided into two areas, analytical methods and experimental procedures.

Analytical Methods

1. The development of a coupled theory for heat conduction and fluid dispersion under a thermally induced pore pressure gradient is warranted for a better understanding of the transient state heat transmission characteristics of a porous medium.
2. Numerous correlation equations for estimating thermal properties have been proposed by various researchers (e.g. Somerton, Keese and Chu, 1974 on Kern River oil sands). It would be a good exercise to investigate the applicabilities of such equations to other oil sands and to identify the key parameters required for a general correlation. The investigation has not been done because the number of thermal tests performed are limited. In order to establish more general correlation equations for thermal property approximation, more thermal testing on oil sands with different compositions are necessary.

Experimental Procedures

1. Considering the breakage of probes, it is recommended that plasma-welding be employed for all sealing and attachment purposes. To determine the exact heated length of a thermal conductivity probe, an x-ray on the entire length of the probe is also suggested to be carried out prior to use.

2. To avoid breakage of the porous stones under compression, it is recommended that higher compression resistant porous stones with low thermal conductivity be used.
3. Since some of the components of the thermal test cell have temperature ratings up to about 220 °C only, it is not recommended that the present apparatus be tested above this temperature. A new design with higher temperature resistant components is warranted for thermal testing exceeding this limit.
4. Most of the tests were carried out under a back pore fluid pressure of approximately 2000 kPa and a vertical confining pressure of about 4000 kPa. The durability of the thermal test cell components, particularly the probe heater, under higher pressures has yet to be checked.
5. It has been found that the present datalogger is not quite adequate for thermal property testing. A more capable system that can scan more channels in a shorter period of time is desired. Most importantly, a more accurate built-in timing device in the system is required for better time reporting. The present system sometimes scans data 1 to 3 seconds faster than specified. Since accurate thermal conductivity and thermal diffusivity evaluations rely heavily on the time-temperature record, higher precision in data recording is required.
6. Although the method used in approximating the densities

of a specimen at various temperatures during thermal testing (Appendix D) should be appropriate, it is recommended that an actual calibration of the thermal testing assembly for density measurement be made. This will require accurate measurements from the LVDT and volume change devices as well as a knowledge of the thermal expansion coefficients of the specimen and the thermal test cell components.

7. The effects of variations in the other parameters (listed in Table 1.1 but not covered in this study) on the thermal properties of oil sands merit further investigation. These parameters are mineralogy, grain size distribution, uniformity and pressure. Oil sand samples from different deposits should be tested for a more objective comparison.

8. To better simulate *in situ* stresses acting on an undisturbed oil sand specimen, it is recommended that a more flexible membrane such as a thin copper jacket be used in place of the thick confining cylinder. Lateral confining pressure may then be applied through the silicon oil fluid inside the high temperature/pressure cell. The exterior sample surface may be heated by coil heaters wound inside a ceramic shroud for thermal diffusivity measurements. One may refer to a paper presented by Enniss *et al* (1978) for details of such a set-up.

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APPENDIX A - Thermal Properties of Other Relevant Materials

Thermal Properties of Constituents of Oil Sands

The principal minerals found in Alberta oil sand deposits are listed in Table A.1 (Bayliss and Levinson, 1976). Dusseault and Morgenstern (1978) found that the solid phase of Athabasca oil sand consists of about 95 % quartz, 3 % feldspar, 1 % mica and 1 % clays. According to Agar's (1984) analyses, the minerals in the Saline Creek oil sand cores used for this study are about 97 % coarse-grained and 3 % fine-grained. The coarse minerals are predominantly quartz grains with traces of pyrite and brookite while the fines are mainly kaolinite and illite. In addition to the solid phase, bitumen (oil), air (gases), and water together constitute the rest of the oil sand structure.

The thermal properties of quartz crystals have been studied by many investigators. Birch and Clark (1940) reported the thermal conductivity of quartz single crystals, both parallel and perpendicular to the optic axis, for temperatures ranging from 0 to 400 °C. Ratcliffe (1958) proposed the following equation for the evaluation of thermal conductivity of crystalline quartz over the temperature range of 0 to 100 °C.

$$k_+ = 1 / (0.14498 + 5.7801 \times 10^{-4}\ T) \qquad 0 \le T \le 100 \qquad \text{A.1}$$

where: k_+ = Thermal conductivity of crystalline quartz (W/m °C)

T = Temperature (°C)

A comparison with Birch and Clark's data indicates that equation A.1 is suitable for thermal conductivity values perpendicular to the optic axis of the quartz crystal. De Vries (1966) noted the average thermal conductivity of crystalline quartz as being the sum of one third of its conductivity parallel to the optic axis and two thirds of that perpendicular to the axis. The author reported average conductivity values of quartz at 20 °C, 40 °C, 60 °C and 75 °C. In the *Handbook of Physical Constants*, Clark (1966) presents thermal conductivity values from various sources. Horai and Simmons (1969) interpolated data from Kaye and Higgins (1926), and Birch and Clark (1940) to obtain the following correlation equations for change in thermal conductivity of crystalline quartz with temperature:

1. Kaye and Higgins

$$k_{-} = 1 / (0.07882 + 4.4807\times10^{-4}\ T)$$
$$0 \le T \le 100 \qquad \text{A.2}$$
$$k_{+} = 1 / (0.14283 + 6.1909\times10^{-4}\ T)$$

2. Birch and Clark

$$k_{-} = 1 / (0.08794 + 3.5755\times10^{-4}\ T)$$
$$0 \le T \le 100 \qquad \text{A.3}$$
$$k_{+} = 1 / (0.14765 + 5.5126\times10^{-4}\ T - 2.9139\times10^{-7}\ T^2)$$

where: k_{-} = Thermal conductivity of crystalline quartz parallel to the optic axis (W/m °C)

k_{+} = Thermal conductivity of crystalline quartz perpendicular to the optic axis (W/m °C)

T = Temperature (°C)

In chapter 12 of the data book on *Physical Properties of Rocks and Minerals* (1981), Roy, Beck and Touloukian included plots depicting the temperature dependence of thermal conductivity, thermal diffusivity and specific heat of crystalline quartz. De Vries (1966) reported a specific heat of 0.756 J/g °C and a density of 2.66 g/cm^3 for quartz at 10 °C. Birch and Clark (1940) used a density value of 2.652 g/cm^3 while Horai and Simmons (1969) recommended 2.647 g/cm^3. Generally, a specific gravity of 2.65 is assumed.

A plot summarizing the thermal conductivity values of quartz reported by the above researchers is presented in Figure A.1. Figures A.2 and A.3 show the changes in thermal diffusivity and specific heat of quartz with temperature respectively.

It has been widely accepted that the thermal conductivity of soil/rock that contains quartz minerals is highly dependent on its content. Figure A.4 examplifies the significance of quartz content on the thermal conductivity of granitic rock cores (Eckstein, Dahl and Vitaliano, 1983). Since over 90 % of the constituents of the solid phase of oil sand is quartz, thermal conductivity of the solids is governed to a great degree by the quartz sand. The above statement can easily be justified by comparing the thermal conductivity values of clay minerals, feldspar, mica, calcite etc. with that of quartz.

De Vries (1966) reported the thermal conductivity of clay minerals as 2.931 W/m °C. Martinez-Baez (1980) used 2.769 W/m °C for the thermal conductivity of kaolinite. Roy, Beck and Touloukian (1981) suggested the thermal conductivity of feldspars to be 2.5±1.5 W/m °C. Martinez-Baez (1980) used 2.146 W/m °C as the value. Horai and Simmons (1969) presented a range of thermal conductivity values for micas from 1.570 to 2.495 W/m °C. The thermal conductivity of calcite has been investigated by many researchers such as Birch and clark (1940), Clark (1966), Horai and Simmons (1969), and Roy, Beck and Touloukian (1981). The values recommended fall within the range of 3.0±0.8 W/m °C. It can be observed that the thermal conductivity of quartz solids is at least two to three times higher than those of the other solid minerals in oil sand. Therefore, it may be reasonably stated that the thermal conductivity of the solid phase of oil sand is close to that of quartz sand.

Thermal diffusivity data on rock forming minerals and other materials are scarce as this thermal property is generally calculated from known values of thermal conductivity, specific heat and density of the materials. Nevertheless, the thermal diffusivity values of quartz, K-feldspar, calcite, illite are found to be 2.29×10^{-6}, 1.53×10^{-6}, 1.39×10^{-6} and 1.90×10^{-6} m^2/s respectively (Wang, Rajeshwar and DuBow, 1979). Roy, Beck and Touloukian's (1981) data book may be consulted for the temperature dependence of the thermal conductivities, thermal diffusivities and specific heats of these and many other rock forming minerals.

De Vries (1966) reported the specific heats of mica, calcite and kaolin to be 0.867, 0.871 and 0.938 J/g °C respectively (at 60 °C). The corresponding solid densities are 2.9, 2.71 and 2.6 g/cm³. At 10 °C, the specific heat and density of clay minerals are reported to be the same as those of quartz. Skauge, Fuller and Hepler (1983) have carried out an extensive study on the specific heats of clay minerals. The values of specific heat found range from 0.742 to 0.931 J/g °C near room temperature. The changes in specific heats of the clay minerals with temperature up to 427 °C were also studied by the authors. Clark (1944) reported that the specific heat of the mineral matter in his oil sand sample was 0.75 J/g°C. Skauge *et al* (1983) measured specific heat capacities of minerals found in oil sands and heavy oil deposits in Athabasca, Cold Lake, Peace River and Grosmont, Alberta, as well as in Zaire, Utah, Malagasy and Nigeria. Correlation equations of specific heat values with temperatures from 27 °C to 427 °C are presented in the paper.

Apart from the solid phase, the thermal properties of the saturating fluids inside the pore space are very significant in determining the thermal properties of the oil sand mass. Density, specific heat and thermal conductivity of air are plotted as functions of temperature in Figures A.5, A.6 and A.7 respectively. The same set of plots are included for water as shown in Figures A.8, A.9 and A.10. The data for the above plots are readily available in handbooks of physics, chemistry and engineering. Ward and Clark (1950) reported that the specific gravity of Athabasca bitumen ranges from 1.002 to 1.027. Kosar (1983) has a plot of the change in density of Athabasca bitumen with temperature as shown in Figure A.11. According to Farouq Ali's lecture notes (1982), the specific heat of oil can be estimated by the following formula:

$$c_o = (1.6848 + 0.00391\ T) / \sqrt{G_o} \qquad \text{A.4}$$

where: c_o = Specific heat of oil (J/g °C)

T = Temperature (°C)

G_o = Specific gravity of oil (dimensionless)

Clark (1944) suggested a specific heat value of 1.47 J/g °C for oil in oil sands for applications from 0 °C to 100 °C. Smith-Magowan, Skauge and Hepler (1982) proposed the following correlation equation for estimating specific heats of Athabasca bitumen:

$$c_b = 1.557 + 5.219\times10^{-3}\ T - 8.686\times10^{-6}\ T^2 \qquad 50 \leq T \leq 300 \qquad \text{A.5}$$

where: c_b = Specific heat of bitumen (J/g °C)

T = Temperature (°C)

Figure A.12 depicts the temperature dependence of Athabasca bitumen according to equation A.5.

Little work has been done in evaluating the thermal conductivity of bitumen. Pfeiffer (1950) suggests that a value of 0.151 W/m °C be used in practice. Deston (1976) proposes 0.137 W/m °C as an average value with 6 % error.

Prowse *et al* (1982) recommends a value of 0.15 W/m °C for Athabasca bitumen based on a study by Lorincz (1980). Bland and Davidson (1967) propose a correlation equation for evaluating the thermal conductivity of hydrocarbon mixtures, oils and petroleum fractions with temperature and specific gravity as follows:

$$k = 0.117\ (1.000 - 0.00054\ T)\ /\ G \qquad \text{A.6}$$

where: k = Thermal conductivity of oil/bitumen (W/m °C)

T = Temperature (°C)

G = Specific gravity of oil/bitumen at 15.4 °C (dimensionless)

Equation A.6 underestimates the thermal conductivity values proposed by Pfeiffer (1950) by about 20 %. Since there is such a great discrepancy, the correlation equation (A.6) should be used with caution. Futher investigation in determining the thermal conductivities of the various hydrocarbons is essential for the development of a more general and accurate correlation equation.

Thermal Properties of Granular and Rock Masses

As discussed in the previous section, the thermal conductivity of quartz crystals is higher than that of most other common rock-forming minerals. Since the silicate forms as the major constituent of sand and other granular and rock masses, the thermal properties of quartz sand masses have been studied rather extensively.

Kersten (1949) studied the thermal conductivities of many types of soils using a steady state coaxial type of thermal testing apparatus. The author reported the thermal conductivities of Ottawa sand and some sandy soil samples as a function of dry density, moisture content and degree of saturation. Figures A.13 and A.14 show the change in thermal conductivity of quartz sand with moisture content and dry density respectively. Figure A.15 is a diagram for rough estimations (±25 %) of the thermal conductivity values of sandy soils according to known values of density, moisture content and degree of saturation. Somerton (1958) measured the thermal properties of a fine sand and a coarse sand with both air and water saturations. The thermal conductivities of the fine sand were found to be 0.627 W/m °C dry and 2.752 W/m °C water-saturated. The corresponding values of the coarse sand were measured to be 0.557 W/m °C and 3.072 W/m °C respectively. Krupiczka (1967) found that his dry sand samples had thermal conductivities of 0.257 to 0.314 W/m °C. The porosities of the samples were 0.41, 0.39 and 0.37. Flynn and Watson (1969) reported 0.38 W/m °C and 0.26 W/m °C as the thermal conductivity values of a 20-30 Ottawa sand with densities of 1.76 g/cm^3 and 1.57 g/cm^3 respectively. Changes in thermal conductivity of the sand as well as other soils and rocks with temperatures up to 1600 °C are also included in the authors' report. Somerton, Keese and Chu (1974) studied thermal conductivities of unconsolidated quartz sands with porosities ranging from 0.30 to 0.50. The values found were 0.254 to 0.575 W/m °C for dry sand and 1.419 to 3.756 W/m °C for brine-saturated sand. Poulsen *et al* (1981) suggested that the thermal conductivity of quartz sand to be 2.684 ± 0.032 W/m °C.

It can be observed that the thermal conductivity of a quartz sand mass is quite a bit lower than that of a pure quartz crystal. The introduction of a saturating medium of lower thermal conductivity to the quartz crystal matrix greatly reduces the overall thermal conductivity of the mass. Thermal conductivity of water is higher than that of air. Therefore, a higher thermal conductivity of the granular mass can be envisaged if the mass is saturated with water rather than air.

The specific heats of a fine sand sample was found to be 0.766 J/g °C dry and 1.419 J/g °C water-saturated (Somerton, 1958). Those of a coarse sand are 0.766 J/g °C and 1.319 J/g °C respectively. It should not be surprising to note that the specific heats of the two dry sand samples of different grain sizes and densities are the same. According to Smith-Magowan, Skauge and Hepler (1982) and many other investigators, the specific heats of a material may be calculated as the sum of the weighted average of the specific heats of its constituents. Since the weight of air is negligible, the specific heat of the quartz sand mass should thus be close to that of a quartz crystal. A comparison of the specific heats of the mass and the crystal indicates that this assumption is true. De Vries (1966) also reported the specific heat of a 20-30 Ottawa sand as 0.766 J/g °C at 37.8 °C. However, the value of a graded Ottawa sand was found to be 0.737 J/g °C at the same temperature. Haynes, Carbee and Vanpelt (1980) measured a specific heat value of 0.816 J/g °C (at 20 °C) for another 20-30 Ottawa sand. A wet sample with 26.9 % moisture content was reported to have a specific heat of 1.486 J/g °C.

Another type of quartz sand that is of interest to the current research is that of an extracted oil sand or an oil sand tailings sand. Somerton, Keese and Chu (1974) measured the thermal conductivities of dry extracted oil sands (from Kern River, Midway-Sunset, Huntington Beach and Bradley Canyon) to be 0.337 to 0.466 W/m °C. The porosities were from 0.31 to 0.45. The thermal conductivities of water-saturated and extracted Kern River oil sands were found to be 2.08 to 2.46 W/m °C with porosities of 0.28 to 0.37. Cervenan, Vermeulen and Chute (1981) have studied the thermal conductivities and specific heats of extracted Athabasca oil sands. With water saturations of 3.3 %, 12.7 % and 62.2 % by weight, thermal conductivities of the samples were determined to be 0.80, 1.24 and 2.39 W/m °C respectively. The corresponding porosities were 0.451, 0.445 and 0.429. The specific heats of two other samples, with water contents of 3 % and 4 % by weight, were determined to be 0.84 and 0.85 J/g °C respectively.

Since the main constituent of the solid phase of the above extracted oil sand samples is quartz, it is as anticipated that the thermal properties of these specimens are comparable to those of the quartz sand samples discussed earlier.

Although it is beyond the scope of the current research to investigate the thermal properties of the soil/rock formations adjacent to the Alberta oil sand deposits, it may be worthwhile to outline some of the thermal properties of the materials for future reference. Tables A.2, A.3, A.4 and A.5 are summaries of the thermal properties of clay, sandstone, shale and limestone respectively. It should be noted that the values are obtained from samples at different geographical regions and thus should not be taken as being applicable to other localities. The information provided may be limited, but it may serve as a starting point for locating the relevant references as well as for future research.

Table A..1 Mineralogical Compositions of Lower Cretaceous Oil Sand Deposits (after Bayliss and Levinson, 1976)

	ATHABASCA DEPOSIT				PEACE RIVER DEPOSIT		WABASCA DEPOSIT				COLD LAKE DEPOSIT		LLOYDMINSTER AREA	
	MCMURRAY FM. 247 samples		CLEARWATER FM. 15 samples		BLUESKY FM./ GETHING FM. 32 samples		WABISKAW MBR. 15 samples		GRAND RAPIDS "A" MBR. 6 samples		CLEARWATER FM./ GRAND RAPIDS FM. 15 samples		DINA FM. 13 samples	
	(Percent of Total Minerals)													
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
QUARTZ	80.	41-97.	63.	21-87.	69.	17-92.	81.	57-96.	66.	55-87.	75.	30-98.	83.	56-95.
POTASH FELDSPAR	2.	0-16.	6.	0-42.	2.	0- 7.	4.	T-20.	10.	0-30.	7.	0-19.	3.	0-23.
PLAGIOCLASE	0.1	0- 8.	3.	0-11.	N		1.	0- 6.	12.	0-41.	7.	0-27.	2.	0- 8.
CALCITE	0.2	0-28.	4.	0-12.	0.5	0- 5.	0.9	0- 9.	0.3	0- 2.	0.1	0- 2.	0.1	0- 1.
DOLOMITE	0.4	0- 9.	4.	0-13.	5.	0-24.	1.	0- 7.	N		0.6	0- 5.	1.	0-16.
SIDERITE	1.	0-20.	2.	0- 4.	N		0.3	0- 2.	3.	0-15.	N		N	
PYRITE/MARCASITE	0.4	0-10.	5.	0-45.	6.	0-62.	1.	0- 4.	1.	0- 8.	0.1	0- 2.	N	
KAOLINITE	9.	1-27.	5.	0-19.	15.	4-27.	7.	2-18.	4.	2- 7.	3.	0-11.	6.	1-15.
MICA	1.	0- 8.	T	0- 2.	0.3	0- 4.	0.8	0- 2.	0.2	0- 1.	0.5	0- 3.	2.	0- 8.
ILLITE	4.	T-10.	6.	1-15.	3.	T-11.	3.	T- 9.	3.	1-10.	3.	T-13.	2.	T- 7.
CHLORITE	N		0.3	T- 4.	N		0.1	0- 1.	N		1.	T- 7.	N	
MONTMORILLONITE	N		1.	T- 7.	N		N		N		3.	0-17.	N	

N = Not detected
T = Trace

Table A.2 Thermal Conductivity of Clay

k, W/m °C		ρ, g/cm³	Reference & Remarks
Air	Water		
-	-	-	Kersten (1949); Includes plots of thermal conductivity against density, moisture content and degree of saturation.
1.47-2.51	1.76-2.68	2.40-2.70	Cermak (1967); Consolidated clay.
-	1.74	-	Evans (1977); Tertiary clay.
1.07-1.08	1.94-2.10	-	Bloomer and Ward (1979)
-	-	-	Farouki (1981); Includes a collection of thermal property data at sub-zero to little above room temperatures.
-	1.34	-	Kristiansen et al (1982)
-	0.82-1.89	-	Kristiansen, Saxov and Balling (1982)

Table A.3 Thermal Properties of Sandstone

k, W/m °C Air	 Water	 Oil	α 10^{-7} m²/s	c_p J/g °C	ρ g/cm³	n %	Reference & Remarks
0.68-4.40	4.40-6.99	1.21-4.40	-	-	-	4.4-36.8	Zierfuss and Van der Vliet (1956)
0.88	2.76	1.36	air 5.5 H_2O 11.0	0.77 1.06	2.08 2.27	19.6	Somerton (1958); Includes temperature dependence of specific heat up to 1000°F (538°C).
0.49	1.82	1.00	air 4.1 H_2O 6.3	0.84 1.57	1.44 1.84	40.0	ditto
1.13-1.38		-	7.1-7.9	-	1.88-2.13	-	Somerton and Boozer (1960)
-	1.47-4.27	-	-	-	-	-	Clark (1966)
1.05-3.06	1.63-3.10	-	-	-	1.97-2.77	0.0-18.0	Cermak (1967)
2.05-2.76		-	-	-	-	-	Miseyenko, Sokolova and Istomin (1972)
1.47-2.34	3.08-5.19	-	-	-	1.84-2.15	16.2-29.2	Anand, Somerton and Gomma (1973)
1.30-2.44	2.25-4.64	-	-	-	-	4.2-29.0	Martinez-Baez (1980); 56-57 °C.
0.47-0.59	2.04-2.27	-	-	-	-	35.0	ditto; Unconsolidated.
4.51-6.12		-	-	-	-	-	Kristiansen et al (1982)
3.71-4.22		-	-	-	-	-	Kristiansen, Saxov and Balling (1982)

Table A.4 Thermal Properties of Shale

k, W/m °C		α	c	ρ	n	
Air	Water	10^{-7} m²/s	J/g °C	g/cm³	%	Reference & Remarks
1.04	1.69	air 5.6 H₂O 7.9	0.80 0.89	2.32 2.39	7:1	Somerton (1958); Includes temperature dependence of specific heat up to 1000°F (538°C).
-	1.45	200°C 7.8	-	2.12	-	Somerton and Boozer (1960)
1.17-2.89		-	-	-	-	Claek (1966)
0.87-1.04	1.2101.38	-	-	air 2.20 H₂O 2.35	-	Anand, Somerton and Gomma (1973); 70-250 °F (21-121 °C).
1.40-2.00		-	-	-	-	Evans (1976)
1.52	2.37	-	-	-	14.8	Martinez-Baez (1980); 56-57 °C.
1.35	1.99	-	-	-	14.8	ditto; 124-125 °C.

Table A.5 Thermal Properties of Limestone

k, W/m °C Air	 Water	α 10^{-7} m²/s	c J/g °C	ρ g/cm³	n %	Reference & Remarks
–	2.72	–	–	–	–	Birch and Clark (1940); Includes temperature dependence of thermal conductivity up to 200 °C.
0.92-2.60	1.59-3.81	–	–	–	4.9-36.9	Zierfuss and Van der Vliet (1956)
1.70	3.55	air 9.2 H_2O 13.0	0.85 1.11	2.19 2.39	–	Somerton (1958)
1.56	–	93°C 8.4	–	2.25	–	Somerton and Boozer (1966)
–	1.97-3.35	–	–	–	–	Clark (1966)
2.50-2.70	2.50-2.80	–	–	2.64-2.75	0.0-1.0	Cermak (1967)
–	2.22-2.77	7.2	–	–	–	Moiseyenko, Sokolova and Istomin (1972)
2.40-3.00	2.90-3.10	–	–	–	–	Thomas, Frost and Harvey (1973); 40.5°C.
–	–	11.4	–	–	–	Hanley, Dewitt and Roy (1978); Includes temperature dependence of thermal conductivity up to 1000 K (727°C).
1.80-2.90	–	3.7-8.4	0.86±0.05	–	–	Roy, Beck and Touloukian (1981); Includes plots of thermal conductivity Vs temperature up to 627°C, thermal diffusivity and specific heat Vs temperature up to 927°C.
1.99-3.30	2.52-3.34	–	–	–	–	Poulsen et al (1982)
–	2.70-2.82	–	–	–	–	Kristiansen et al (1982)
–	2.22-2.67	–	–	–	–	Kristiansen, Saxov and Balling (1982)
1.27-1.63	–	–	0.67-0.80	2.71	–	Mongelli, Loddo and Tramacere (1982); 20-240 °C.
–	–	6-12	–	–	–	Lo and Wai (1982); 20-320 °C.

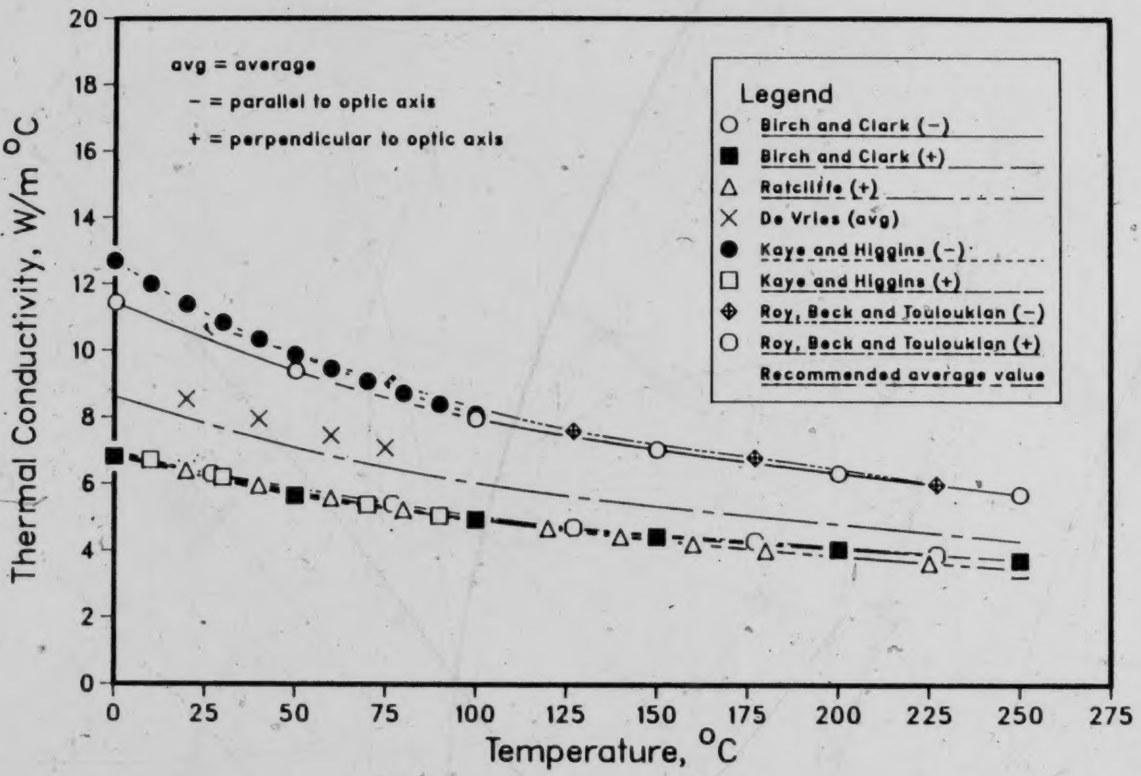


Figure A.1 Change in Thermal Conductivity with Temperature, Crystalline Quartz

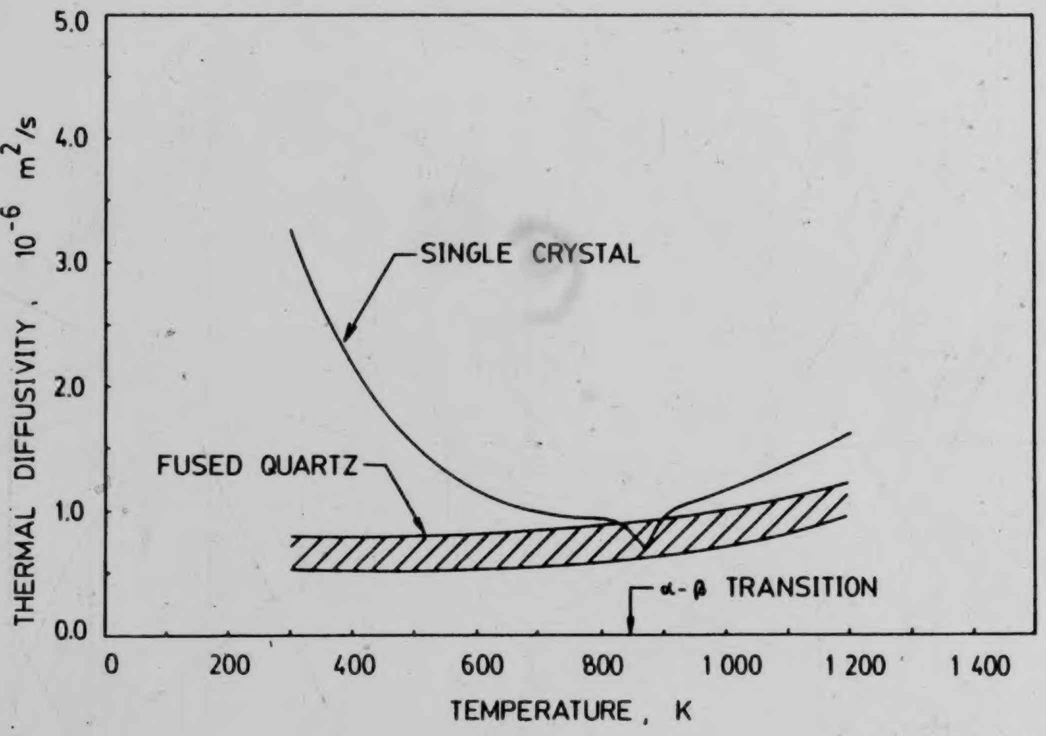


Figure A.2 Change in Thermal Diffusivity with Temperature, Quartz (after Roy, Beck and Touloukian, 1981)

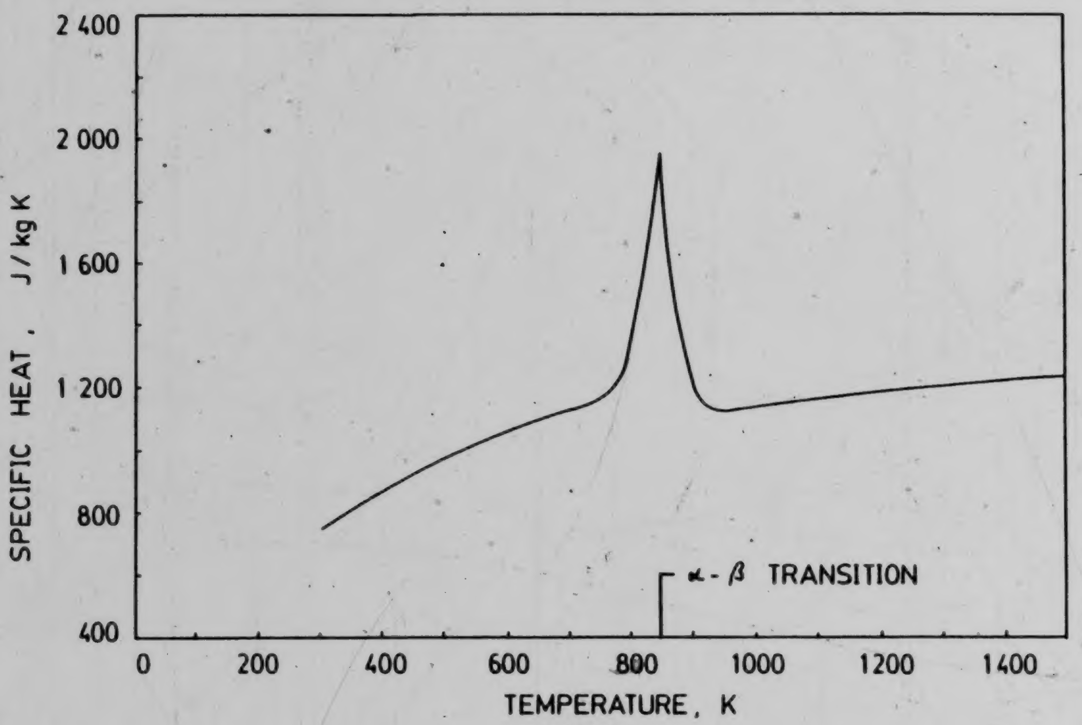


Figure A.3 Change in Specific Heat with Temperature, Quartz
(after Roy, Beck and Touloukian, 1981)

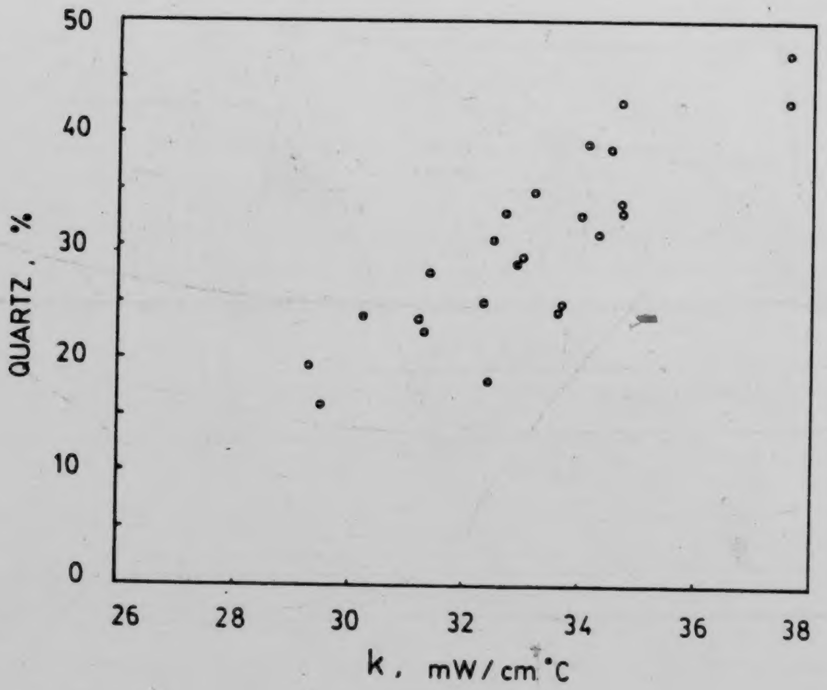


Figure A.4 Dependence of Thermal Conductivity with Quartz Content (after Eckstein, Dahl and Vitaliano, 1983)

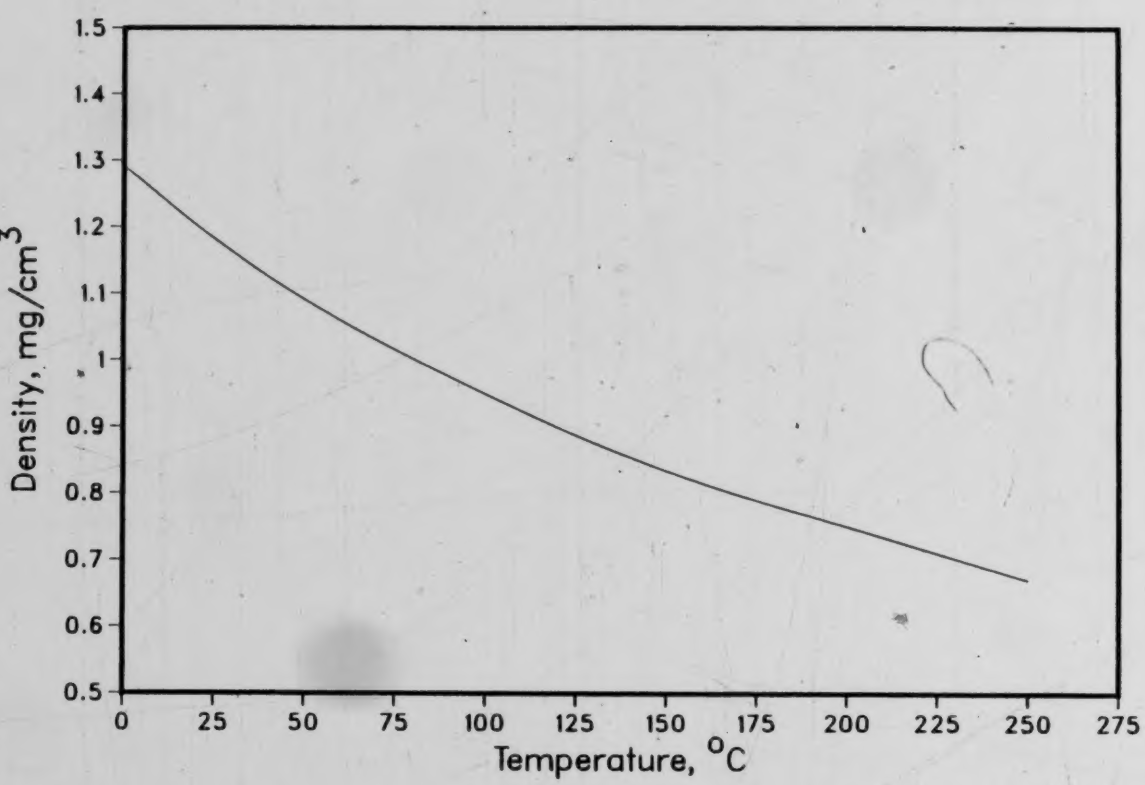


Figure A.5 Change in Density with Temperature, Air

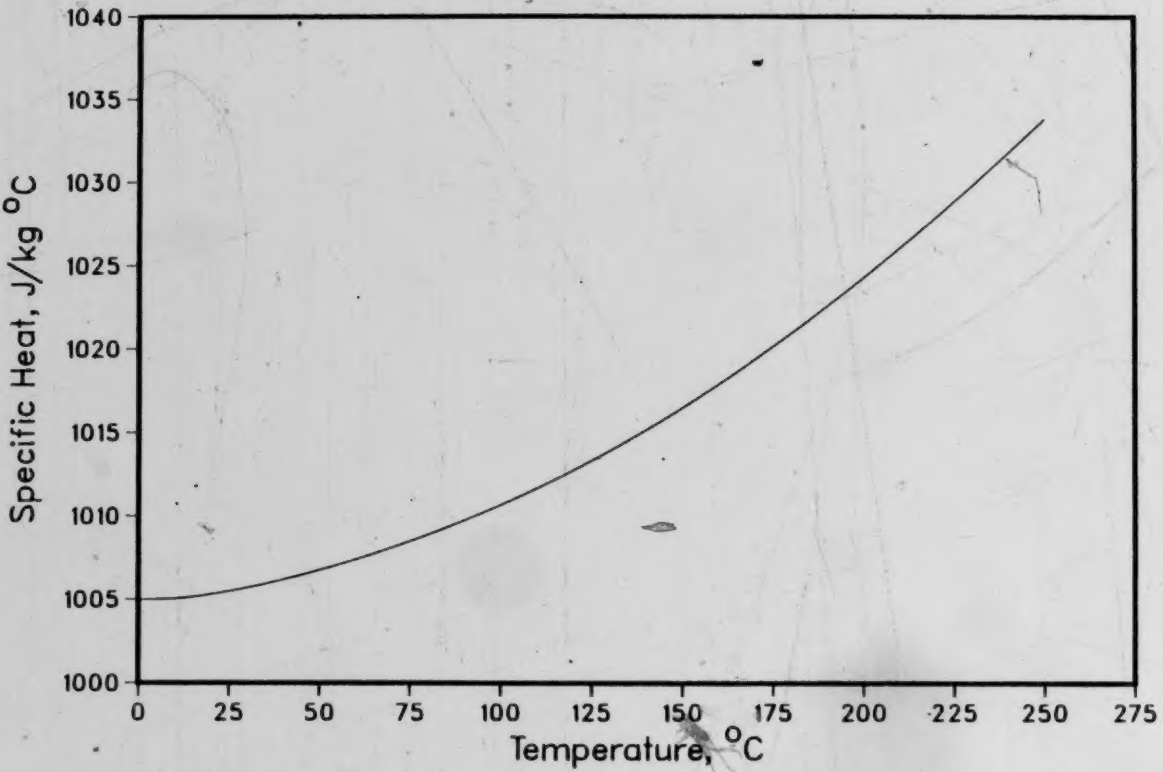


Figure A.6 Change in Specific Heat with Temperature, Air

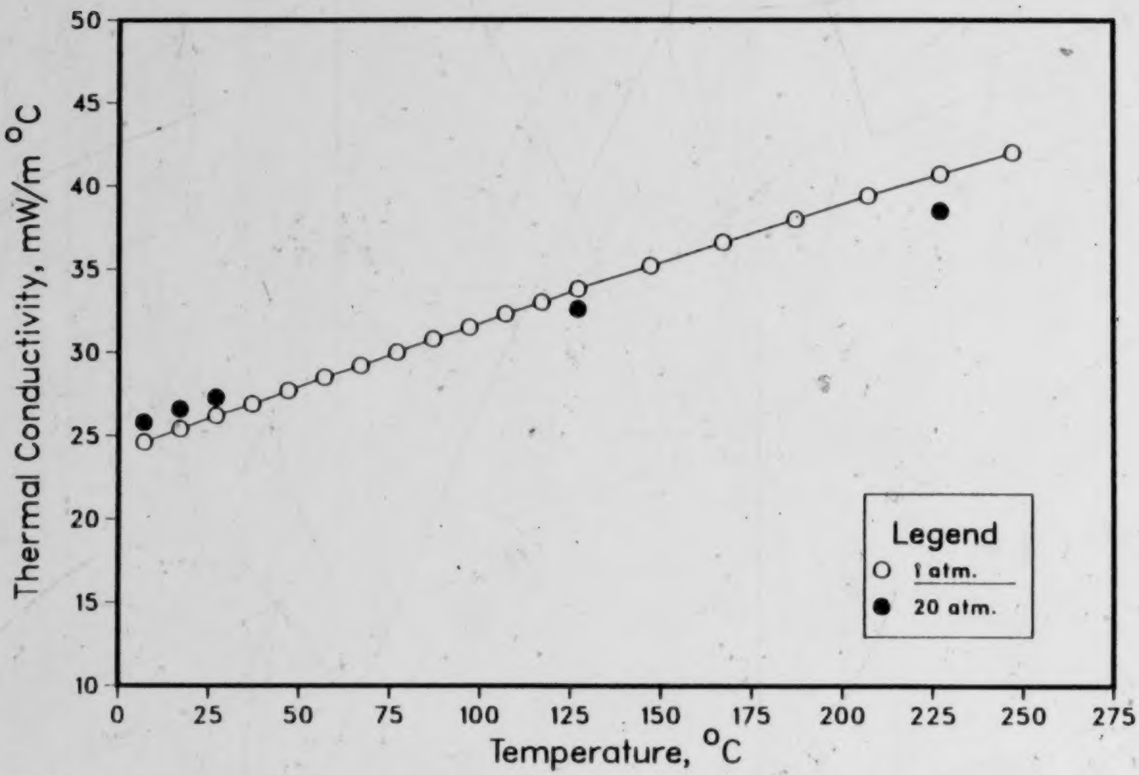


Figure A.7 Change in Thermal Conductivity with Temperature, Air

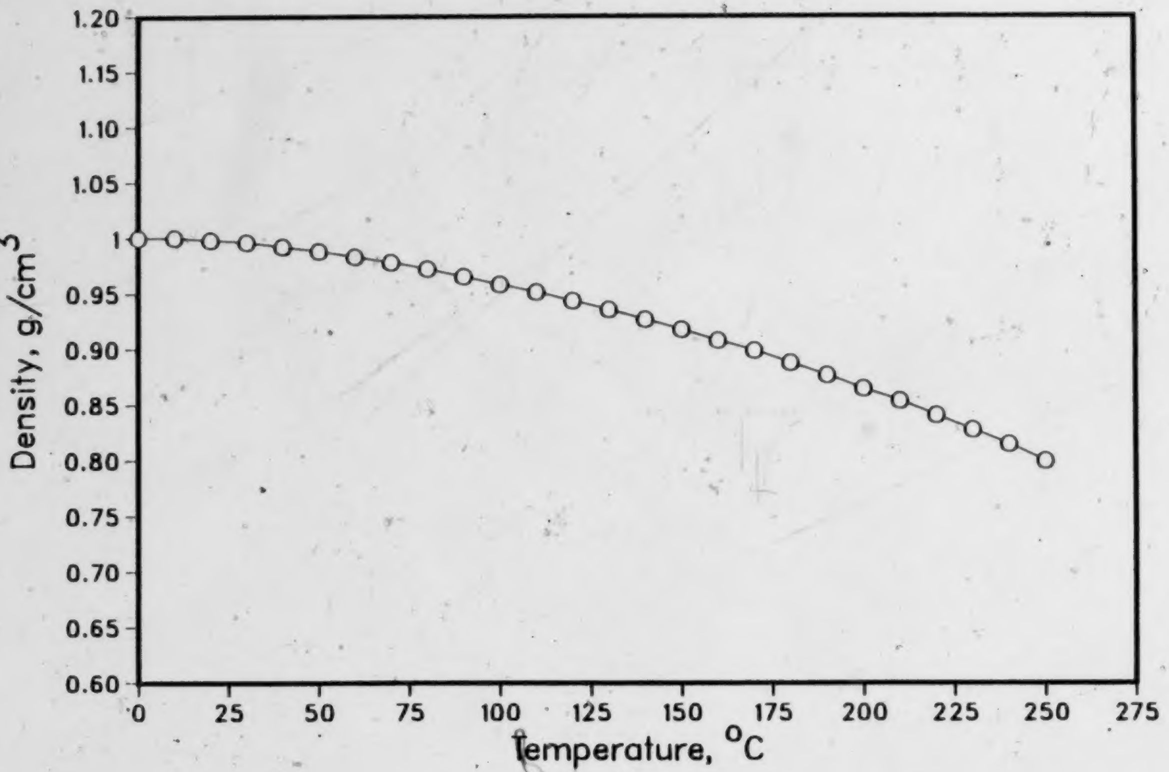


Figure A.8 Change in Density with Temperature, Water

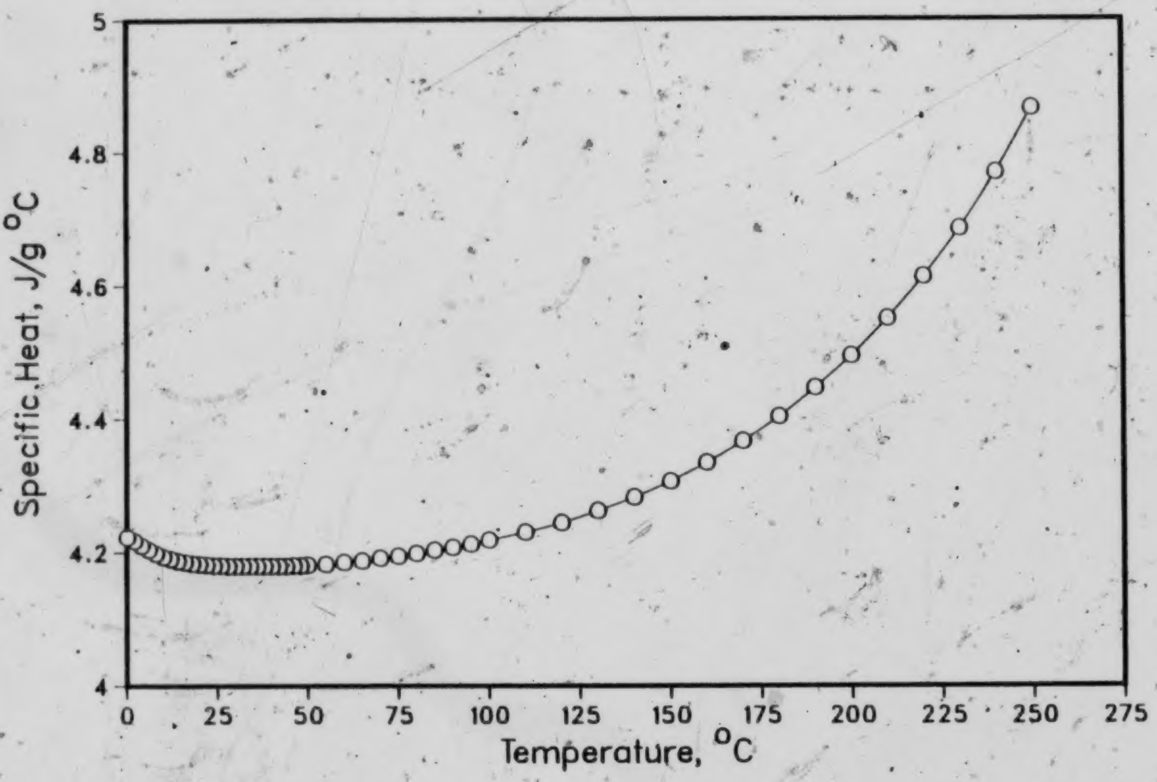


Figure A.9 Change in Specific Heat with Temperature, Water

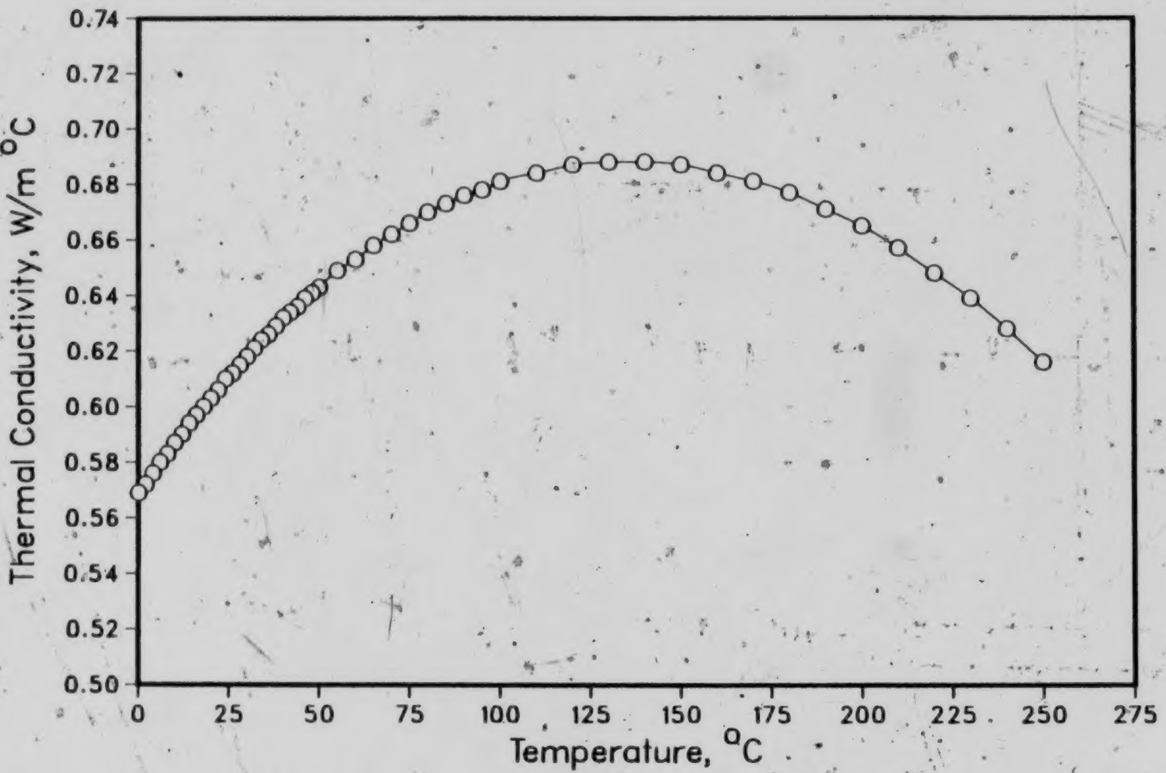


Figure A.10 Change in Thermal Conductivity with Temperature, Water

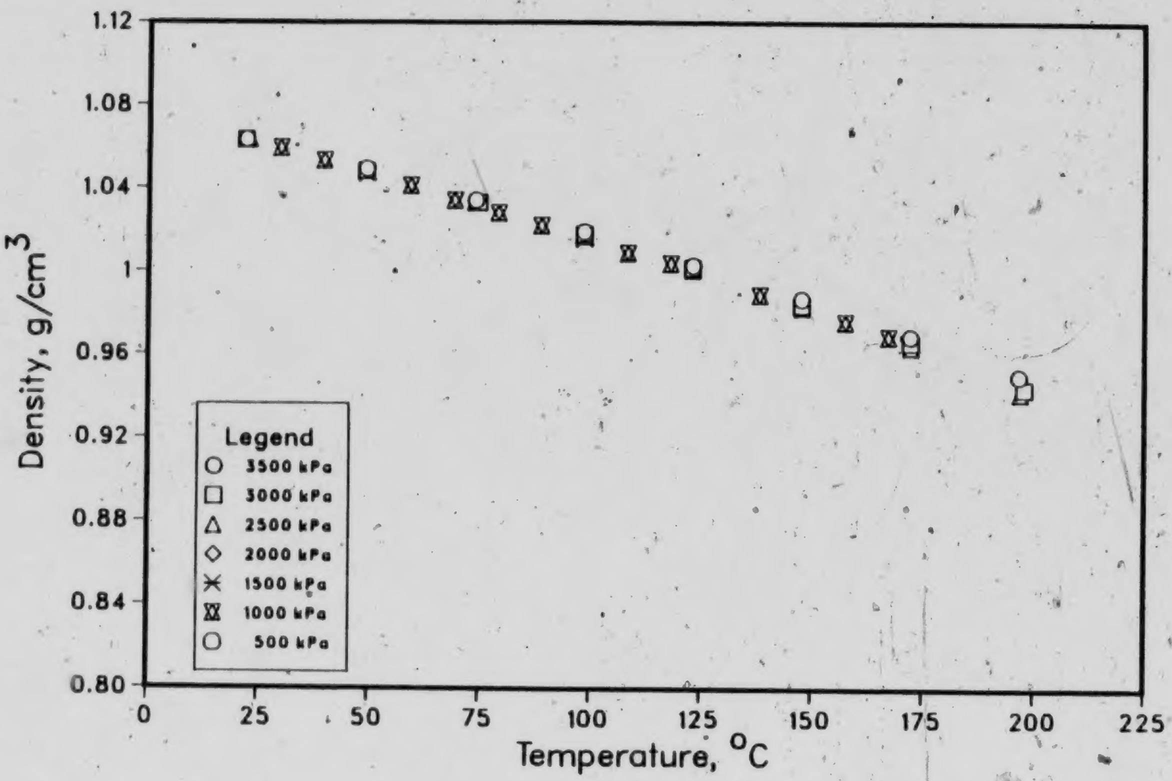


Figure A.11 Change in Density with Temperature, Bitumen (after Kosar, 1983)

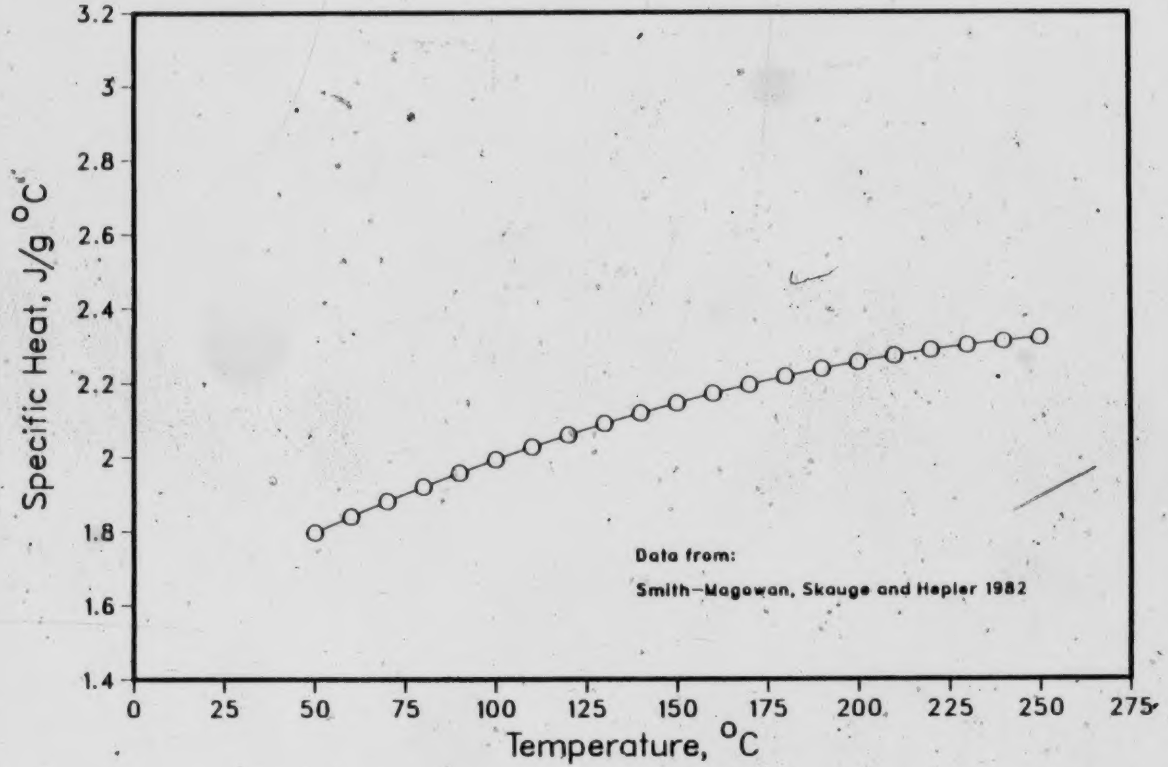


Figure A.12 Change in Specific Heat with Temperature, Bitumen

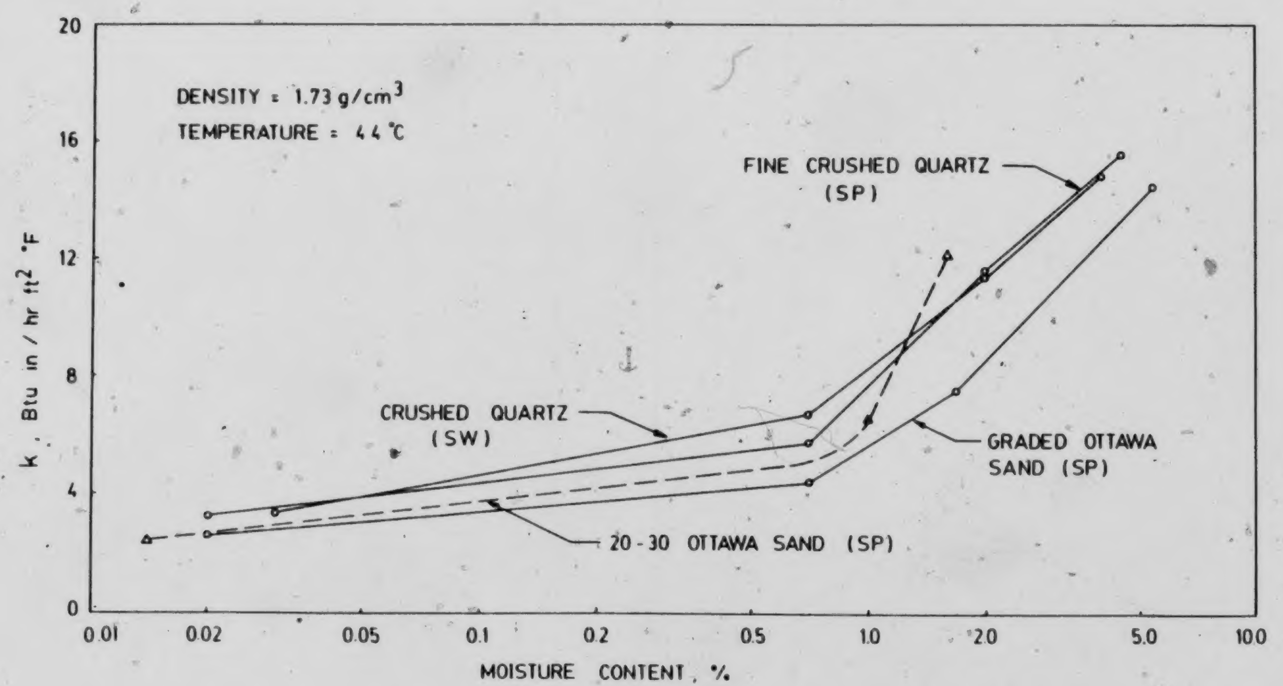


Figure A.13 Change in Thermal Conductivity with Moisture Content, Quartz Sand (after Kersten, 1949)

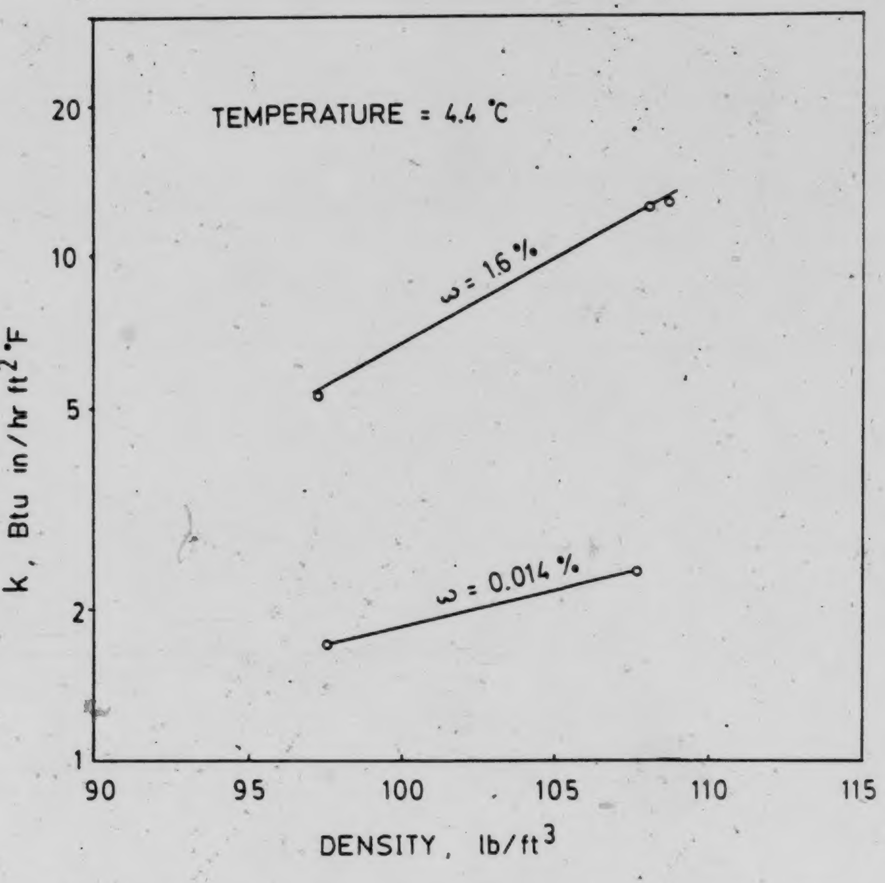


Figure A.14 Change in Thermal Conductivity with Density, Ottawa Sand (after Kersten, 1949)

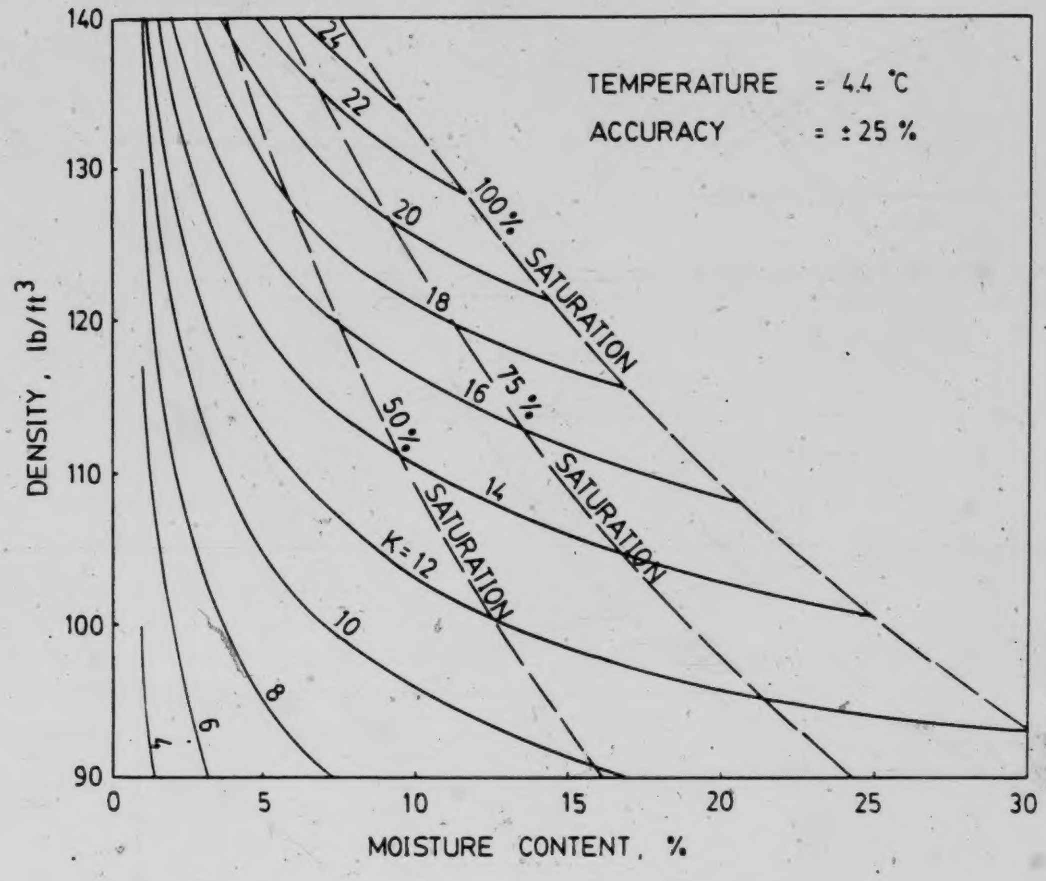


Figure A.15 Diagram of Thermal Conductivity for Sandy Soils (after Kersten, 1949)

APPENDIX B - Derivation of Thermal Diffusivity Equation

Equation 3.15 (Chapter 3):

$$T = \frac{2\alpha}{R_0} \sum_{n=1}^{\infty} e^{-\alpha\delta_n^2 t} \frac{\delta_n J_0(r\delta_n)}{J_1(R_0\delta_n)} \int_0^t e^{\alpha\delta_n^2\lambda} \phi(\lambda)\, d\lambda \tag{1}$$

Let $\phi(t) = A_0 + A_1 t + A_2 t^2 + A_3 t^3 + A_4 t^4 + A_5 t^5 + A_6 t^6 + A_7 t^7$ (2)

and consider the integral $\int_0^t e^{\alpha\delta_n^2\lambda} \phi(\lambda)\, d\lambda$ (3)

Set $a_n = \alpha\delta_n^2$ (4)

Given the general integration formula:

$$\int x^n e^{ax}\, dx = \frac{1}{a} x^n e^{ax} - \frac{n}{a} \int x^{n-1} e^{ax}\, dx \tag{5}$$

Substitute equations (2) and (4) into (3):

$$\int_0^t e^{a_n\lambda} (A_0 + A_1\lambda + A_2\lambda^2 + A_3\lambda^3 + A_4\lambda^4 + A_5\lambda^5 + A_6\lambda^6 + A_7\lambda^7)\, d\lambda$$

$$= \frac{1}{a_n} \Big[(e^{a_n t} - 1)\left(A_0 - \frac{W_1}{a_n}\right) + e^{a_n t} (W_1 t + W_2 t^2 + W_3 t^3 + W_4 t^4 + W_5 t^5 + W_6 t^6 + A_7 t^7) \Big] \tag{6}$$

Where W_1, W_2, W_3, ..., W_6 are as defined in Equation 3.23 of Chapter 3.

Substituting (6) into (1) and setting $\beta_n = R_0\delta_n$, Equation 3.23 results.

APPENDIX C - Specifications of Thermal Test Cell Components

Component	**Specifications**
Top Caps	316 stainless steel; 76.1 mm ø x 44.4 mm thick; two 'O'-ring grooves around circumference; two built-in drainage/pressure ports.
	Roulon-A from JOHNSTON INDUSTRIAL PLASTICS; 76.1 mm ø x 23.8 mm thick; properties as shown in Table C1.
Porous Stone	Bauxelite sandstone from M & L TESTING EQUIPMENT CO. LTD.; 76.1 mm ø x 3.3 mm thick.
Base Block	Roulon-A from JOHNSTON INDUSTRIAL PLASTICS; 76.1 mm ø x 33.3 mm thick with cavity filled with Sauereisen cement (#30, k = 0.72 W/m °C); two built-in drainage/pressure ports.
Base Platen	316 stainless steel; 76.1 mm ø x 19.1 mm at top and 101.6 mm ø x 25.4 mm at bottom; two 'O'-ring grooves around top circumference; two built-in drainage/pressure ports.
'O'-Rings	High temperature #232 'O'-rings from VITON; 3.2 mm diameter.
Confining Cylinder	316 stainless steel; seamless; 76.2 mm i.d., 88.9 mm o.d.; 254 mm long.
Heating Jacket	Silicon rubber jacket from WATLOW; 120 V, 646 W (8406C, #10012980).
Thermocouples	Iron-constantan (type J) thermocouples from ALLTEMP SENSORS; stainless steel sheath; 1.6 mm and 3.2 mm o.d. for internal and external thermocouples respectively.
Probe Heater	3.2 mm diameter heaters from WATLOW; stainless steel sheath; 120 V; 90 W and 400 W for heated lengths of 115.9 mm and 146.1 mm respectively.
Fittings	316 stainless steel fittings from SWAGELOK; 3.2 mm N.P.T.

Table C.1 Thermophysical Properties of Roulon-A

PROPERTY	VALUE
Specific Gravity	2.24 - 2.28
Tensile Strength	1400 - 1500 psi (9.7 - 10.3 MPa)
Elongation	50 -300 %
Compressive Strength (1% strain)	1200 psi (8.3 MPa)
Stiffness in Flexure	75000 - 100000 psi (517 - 689 MPa)
Hardness	60 -75 Durometer D
Compressive Creep	
78°F, 2000 psi, 24 hrs	7 %
500°F, 600 psi, 24 hrs	10.5 %
Coefficient of Friction	
Dry Static	0.04 - 0.16
Dry Dynamic	0.12 - 0.19
Lubricated Dynamic	0.04 - 0.06
Linear Coefficient of Thermal Expansion (-22° to +86°F)	1.83×10^{-5} mm/mm / °C
Thermal Conductivity	0.33 W/m °C
Operating Temp. Range	-400 - 550 °F (-240 - 288 °C)
Flammability	Non-flammable
Water Absorption	0 %
Chemical Resistance	Inert to almost all chemicals

APPENDIX D - Sample Calculations

Power supply to thermal conductivity probe

Given the following experimental data (UOSR.C20W):

Heated length of probe, l = 0.1485 m
Voltage across 2 Ω resistor, V_r = 1.171 V
Voltage from power supply unit, V_p = 19.953 V

Electric current running through the system (or 2 Ω resistor),
$i = V_r / R_r = 1.171 / 2 = 0.5855$ A

Noting that $V_p = V_r + V_h + V_l$

where V_h = Voltage across probe heater, and
V_l = Voltage loss along instrument wire lines,

and assuming negligible wire line resistance such that V_l is very small, then

$$V_p = V_r + V_h \quad \text{or} \quad \begin{aligned} V_h &= V_p - V_r \\ &= 19.953 - 1.171 \\ &= 18.782 \text{ V} \end{aligned}$$

Therefore, power at probe heater,
$$\begin{aligned} q &= V_h * i \\ &= 18.782 * 0.5855 \\ &= 10.997 \text{ W} \end{aligned}$$

and power per unit heated length of probe,
$$\begin{aligned} q_l = q / l &= 10.997 / 0.1485 \\ &= 74.05 \text{ W/m} \end{aligned}$$

Change in sample density with temperature

Sample: ROSR

Initial data at 20 °C:
total mass, M_i = 1223.2 g
average height, H_i = 14.955 cm
average area, A_i = 45.5146 cm^2
bulk density, ρ_i = 1.797 g/cm^3

Final data at 20 °C (after first stage of testing):
change in height = 0.15 cm
final height = 14.805 cm

According to Kosar (1983), cumulative volume change of oil sand from 20 °C to 200 °C is about 0.84 %.

Therefore, final height at 200 °C,
H_{200} = 14.805 (1 + 0.0084) = 14.929 cm

change in height with temperature
= (14.929 - 14.955) / (200 - 20) = -1.444×10^{-4} cm/°C

To calculate bulk densities of the sample at various temperatures, the following assumptions are made:

1. height of sample varies linearly with temperature,
2. areal coefficient of expansion of stainless steel (confining cylinder) is 35.6×10^{-6}/°C, and
3. bulk mass of sample remains constant.

At 50 °C:

$$\begin{aligned} A_{50} &= A_{20} + \Delta A \\ &= 45.5146\ (1 + 35.6\times10^{-6}\ (50 - 20)) \\ &= 45.563\ \text{cm}^2 \end{aligned}$$

$$\begin{aligned} H_{50} &= H_{20} + \Delta H \\ &= 14.955 + (-1.444\times10^{-4}\ (50 - 20)) \\ &= 14.951\ \text{cm} \end{aligned}$$

$$\begin{aligned} \text{Therefore, } \rho_{50} &= M_i\ /\ (A_{50} * H_{50}) \\ &= 1.795\ \text{g/cm}^3 \end{aligned}$$

Similarly, densities at 100 °C, 150 °C and 200 °C are calculated to be 1.793, 1.791 and 1.788 g/cm^3 respectively.

Percents by mass of constituents of oil sand

Sample: UOSR

Data from initial extraction prior to testing:

Percent by mass:	Solids	Bitumen	Water
	83.79	14.81	1.40

Original sample:
total mass, Mt = 1353.0 g
total volume, Vt = 650.88 cm^3
bulk density, ρt = 2.079 g/cm^3

Mass of solids, Ms = 1353.0 * 0.8379 = 1133.68 g
Mass of bitumen, Mb = 1353.0 * 0.1481 = 200.38 g
Mass of water, Mw = 1353.0 * 0.0140 = 18.94 g

Assuming the following specific gravities,
Gs = 2.65, and Gb = Gw = 1.0

then the corresponding volumes are calculated as:
Vs = 1133.68 / 2.65 = 427.80 cm^3
Vb = 200.38 / 1.0 = 200.38 cm^3
Vw = 18.94 / 1.0 = 18.94 cm^3

Volume of air, Va = Vt - Vs - Vb - Vw = 3.76 cm^3

Void ratio, e = volume of voids / volume of solids
= (Va + Vb + Vw) / Vs = Vv / Vs = 0.5215

Porosity, n = volume of voids / total volume = 34.3 %

Degree of saturation, S = (Vw + Vb) / Vv = 98.31 %

Bitumen saturation, Sb = Vb / Vv = 89.82 %

Water saturation, Sw = Vw / Vv = 8.49 %

To calculate percents by mass of the constituents at full saturation (100 %), the volume of air inside the sample is assumed to be displaced by water. Therefore, new mass of water added to the sample at full saturation is:

$\Delta M = 3.76\ cm^3 * 1\ g/cm^3 = 3.76\ g$

However, a 1/4-inch hole (area = 0.3167 cm^2) was drilled through the specimen along its longitudinal axis.

Therefore, volume of material removed = 0.3167 * 14.43
=4.570 cm^3

Mass of material removed = 2.079 * 4.570
= 9.50 g

where the mass loss for each constituent is:
sand = 9.50 * 0.8379 = 7.96 g
bitumen = 9.50 * 0.1481 = 1.41 g
water = 9.50 * 0.0140 = 0.13 g

Approximately 5.8 g of dry tailings sand was used to backfill the central hole.

Volume of internal thermocouple = $\pi(1/32)^2(2.875) * (2.52)^3$
= 0.14454 cm^3

Volume of probe heater = $\pi(1/16)^2(2.54)^2 * 14.43$
= 1.14247 cm^3

Therefore, volume of sand used = 4.570 - 0.14454 - 1.14247
= 3.283 cm^3

Dry density of sand = 5.8 / 3.283 = 1.767 g/cm^3

Porosity of sand = 1 - 1.767/2.65 = 33.33 %

Assuming that all of the air voids are filled with water during full saturation:

Volume of air in 1/4-inch hole = 3.283 * 0.3333
= 1.094 cm^3

Volume of air in the rest of the sample
= 3.76 * (650.88 - 4.57)/650.88
= 3.734 cm^3

Therefore, mass of water added
= (1.094 + 3.734) cm^3 * 1 g/cm^3
= 4.828 g

In summary, mass changes of the specimen upon saturation with water are listed below:

	Sand	Bitumen	Water
Original	1133.68	200.38	18.94
1/4-inch hole	- 7.96	- 1.41	- 0.13
Add sand	+ 5.80		
Add water		+ 4.83	
TOTAL	1131.52	198.97	23.64

Therefore, total mass of saturated specimen = 1354.13 g

Percent by mass:	Solids	Bitumen	Water
	83.56	14.69	1.75

New volumes are:
V_s = 1131.52 / 2.65 = 426.99 cm^3
V_b = 198.97 / 1.0 = 198.97 cm^3
V_w = 23.64 / 1.0 = 23.64 cm^3

Total volume = 649.60 cm^3

Saturated density = 1354.13 / 649.60 = 2.085 g/cm^3

Porosity = Vv / Vt = 222.61 / 649.60 = 34.3 %

Degree of saturation (%):	Overall	Bitumen	Water
	100.0	89.38	10.62

Data from extraction after testing sequence:
(Air-flushed sample)

Percent by mass:	Solids	Bitumen	Water
	88.27	7.00	4.73

Total volume of sample, Vt = 649.60 cm^3

Total mass of air-flushed sample = 1131.52 / 0.8827
= 1281.88 g

Mass of solids = 1131.52 g
Mass of bitumen = 1281.89 * 0.0700 = 89.73 g
Mass of water = 1281.89 * 0.0473 = 60.63 g

The corresponding volumes are:
Vs = 1131.52 / 2.65 = 426.99 cm^3
Vb = 89.73 / 1.0 = 89.73 cm^3
Vw = 60.63 / 1.0 = 60.63 cm^3

Volume of air, Va = Vt - Vs - Vb - Vw = 72.25 cm^3

Void ratio, e = Vv / Vs = 0.5213

Porosity, n = Vv / Vt = 34.3 %

Degree of saturation, S = 67.5 %

Bitumen saturation, Sb = 40.3 %

Water saturation, Sw = 27.2 %

To back calculate the percents by mass of the constituents at full saturation, assume that all of the air is replaced by water.

ΔM = 72.25 cm^3 * 1 g/cm^3
= 72.25 g of water

New total mass = 1281.88 + 72.25 = 1354.13 g

Percent by mass:	Solids	Bitumen	Water
	83.56	6.63	9.81

Degree of saturation (%):	Overall	Bitumen	Water
	100.0	40.3	59.7

Another way of approximating the volume of water displaced by air is by actually measuring the amount of water drained out during the air-flushing process. The calculations are shown as follows:

Total volume of water displaced = 101 cm^3

Volume of extraneous water in thermal test cell:
top ports = 2.8 cm^3
base ports = 2.0 cm^3
top and bottom porous stones (1/4-inch thick)
(assume 50% water remained after air-flushing)
= 11.2 cm^3
Sauereisen cement (assume n=30% and 100% water remained)
= 4.6 cm^3
drainage lines = 1.7 cm^3
TOTAL = 22.3 cm^3

Therefore, net volume of water displaced from sample
= 101 - 22.3 = 78.7 cm^3,
which is close to within 10% of the volume of air (72.25 cm^3) calculated from extraction data at the end of the test sequence.

Specific heat calculations (weighted average method)

Sample: UOSM

From Smith-Magowan, Skauge and Hepler (1982), specific heats of the constituents of oil sands may be estimated by the following equations (50 °C ≤ t ≤ 300 °C):

Coarse solids $= 0.738 + 1.518\text{x}10^{-3}t - 2.026\text{x}10^{-6}t^2$

Fine solids $= 0.778 + 1.400\text{x}10^{-3}t - 0.964\text{x}10^{-6}t^2$

Bitumen $= 1.557 + 5.219\text{x}10^{-3}t - 8.686\text{x}10^{-6}t^2$

Specific heats of water at various temperatures may be obtained from Cooper and LeFevre (1970).

From sieve analysis, the solids of the oil sand samples consist of about 97% coarse grains and 3% fines. Therefore, specific heats of the solids at different temperatures are taken as the weighted average of the values obtained from the first two equations listed above.

Specific heats of the oil sand constituents are tabulated below:

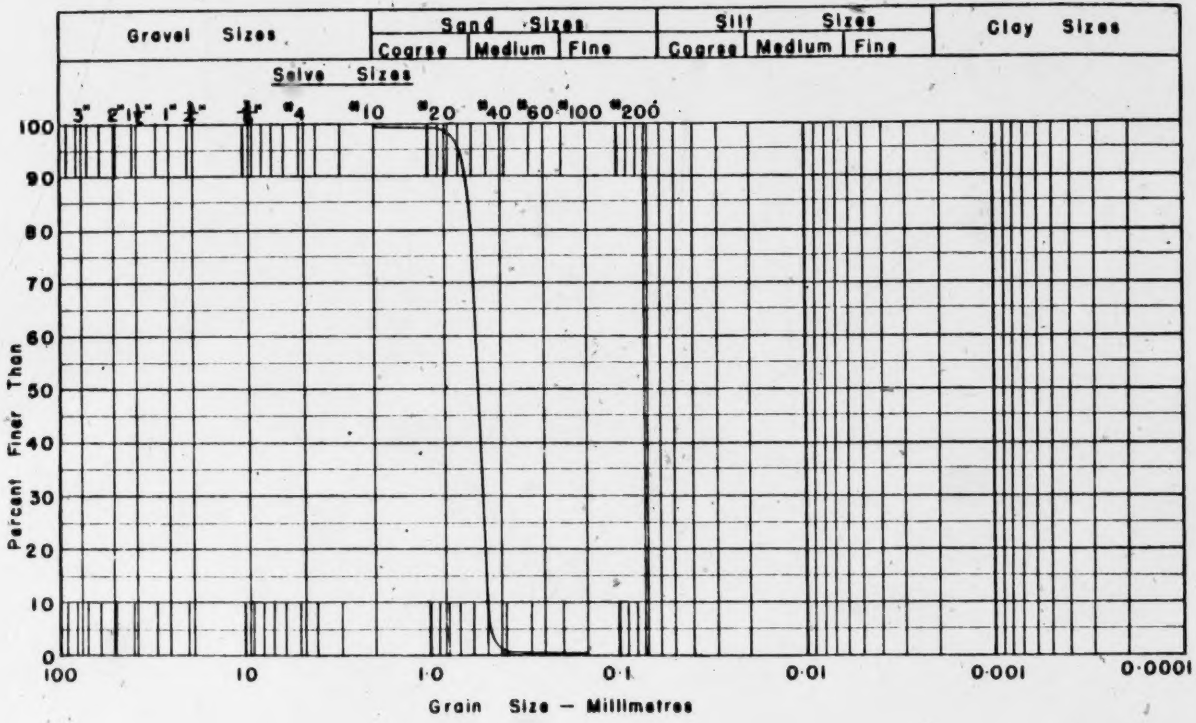
Temperature (°C)	Solids	Bitumen	Water
20	0.76	1.465	4.182
50	0.81	1.796	4.181
100	0.87	1.992	4.218
150	0.92	2.144	4.306
200	0.96	2.253	4.494

Using the weighted average method, specific heat of the medium undisturbed oil sand (UOSM) sample at 20 °C is calculated as shown below:

CONSTITUENTS	c (J/g °C)		% by mass	
solids	0.76	*	83.2	= 0.63
bitumen	1.46	*	12.3	= 0.18
water	4.18	*	4.5	= 0.19
			TOTAL	= 1.00 J/g °C

From experiment,
$k = 2.009$ W/m °C
$\alpha = 10.8\text{x}10^{-7}$ m²/s
$\rho = 2.07\text{x}10^{6}$ g/m³
therefore, c = 0.90 J/g °C (Equation 3.7)

APPENDIX E - Grain Size Distribution

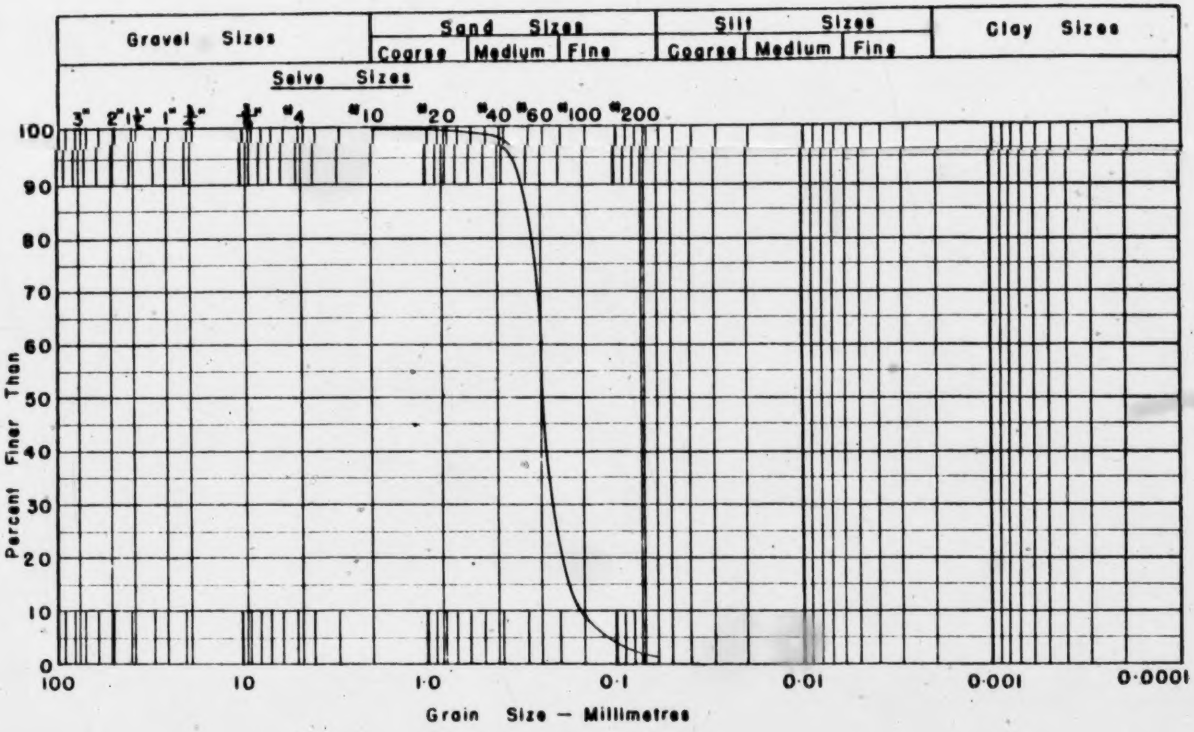


D_{10}= 0.51mm

D_{60}= 0.60mm

C_u = 1.18

Figure E.1 Grain Size Distribution, 20-30 Ottawa Sand

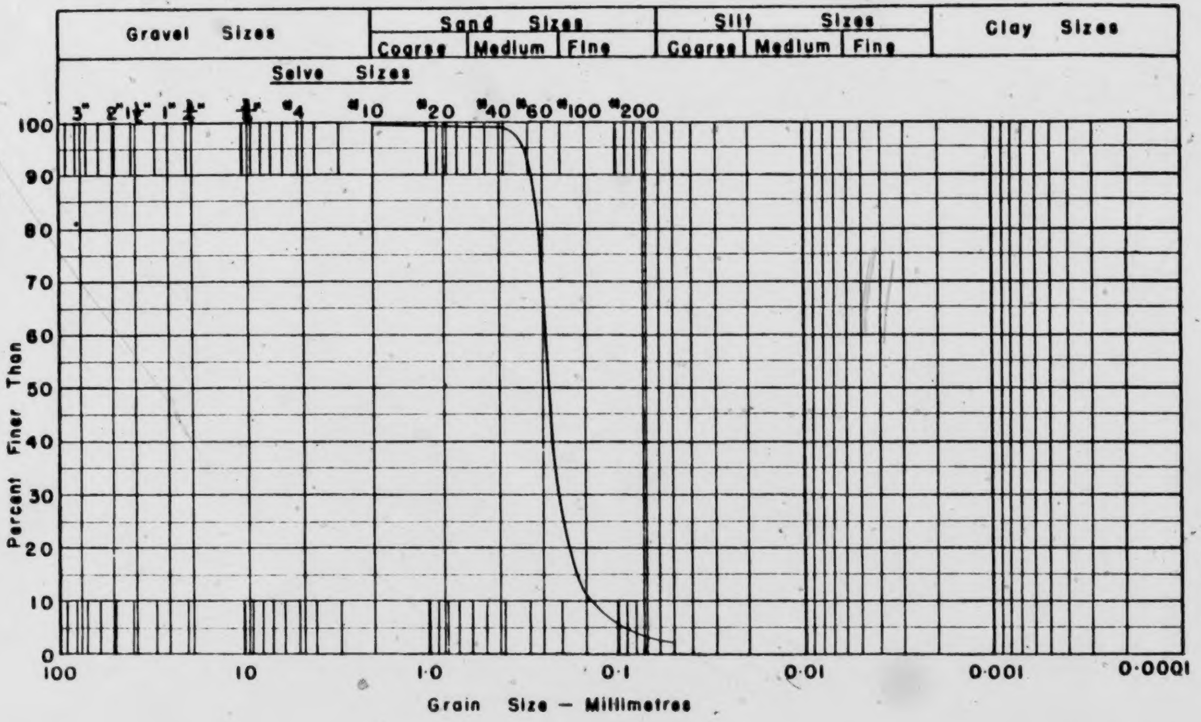


D_{10}= 0.154mm

D_{60}= 0.25 mm

C_u = 1.62

Figure E.2 Grain Size Distribution, Tailings Sand

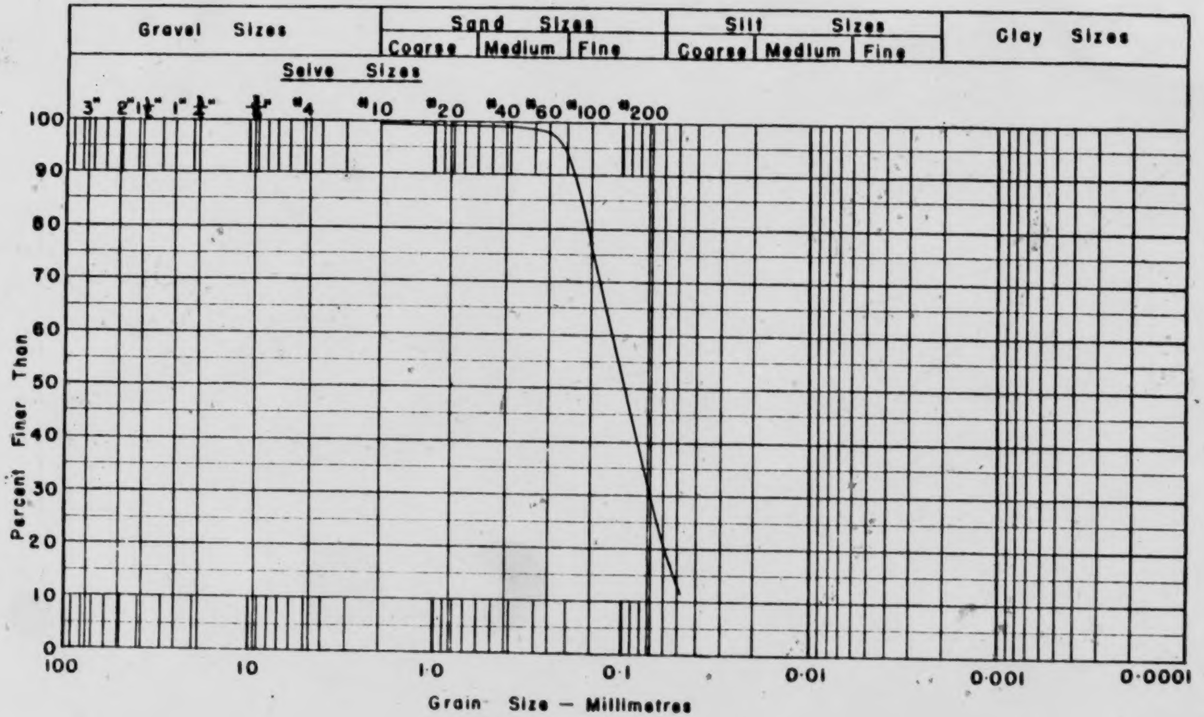


D_{10}= 0.14mm

D_{60}= 0.24mm

C_u = 1.71

Figure E.3 Grain Size Distribution, Saline Creek Oil Sand



D_{10}= 0.046mm

D_{60}= 0.12 mm

C_u = 2.61

Figure E.4 Grain Size Distribution, Oil Sand from Syncrude Site

APPENDIX F - Sample Thermal Conductivity and Diffusivity Data

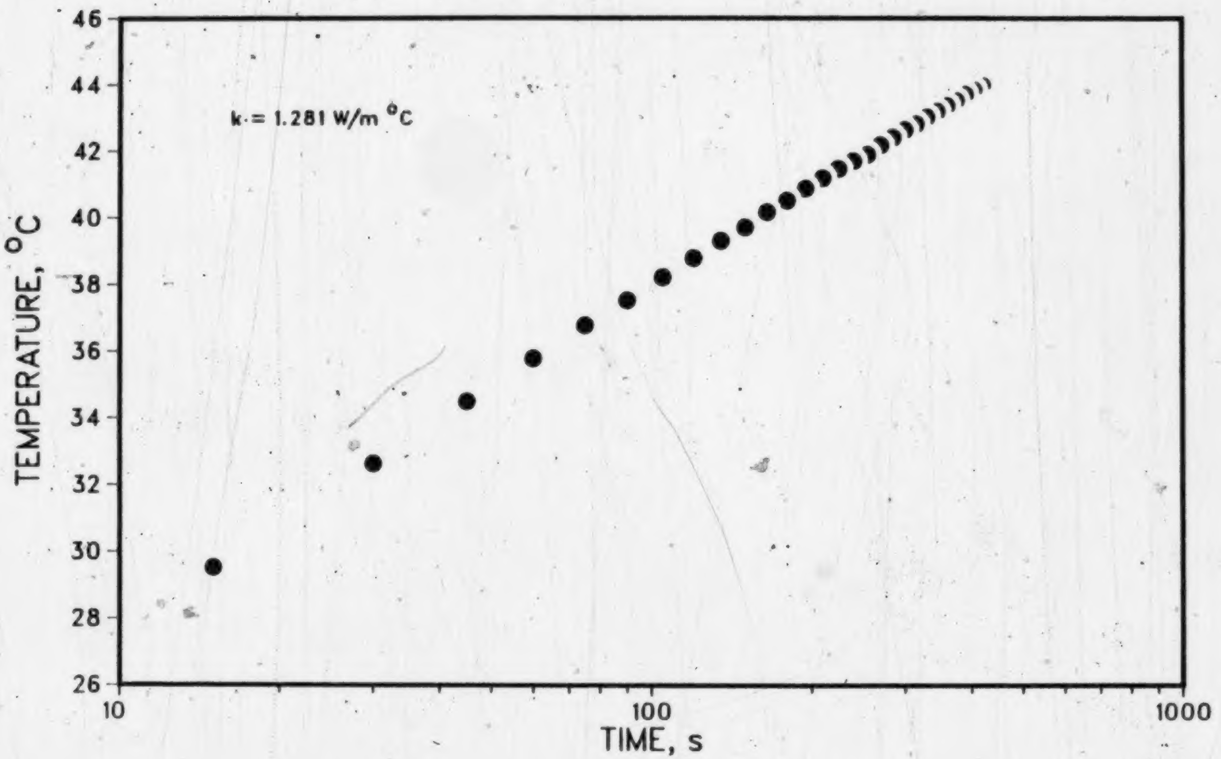


Figure F.1 Thermal Conductivity Test Data, ROSR-C20A

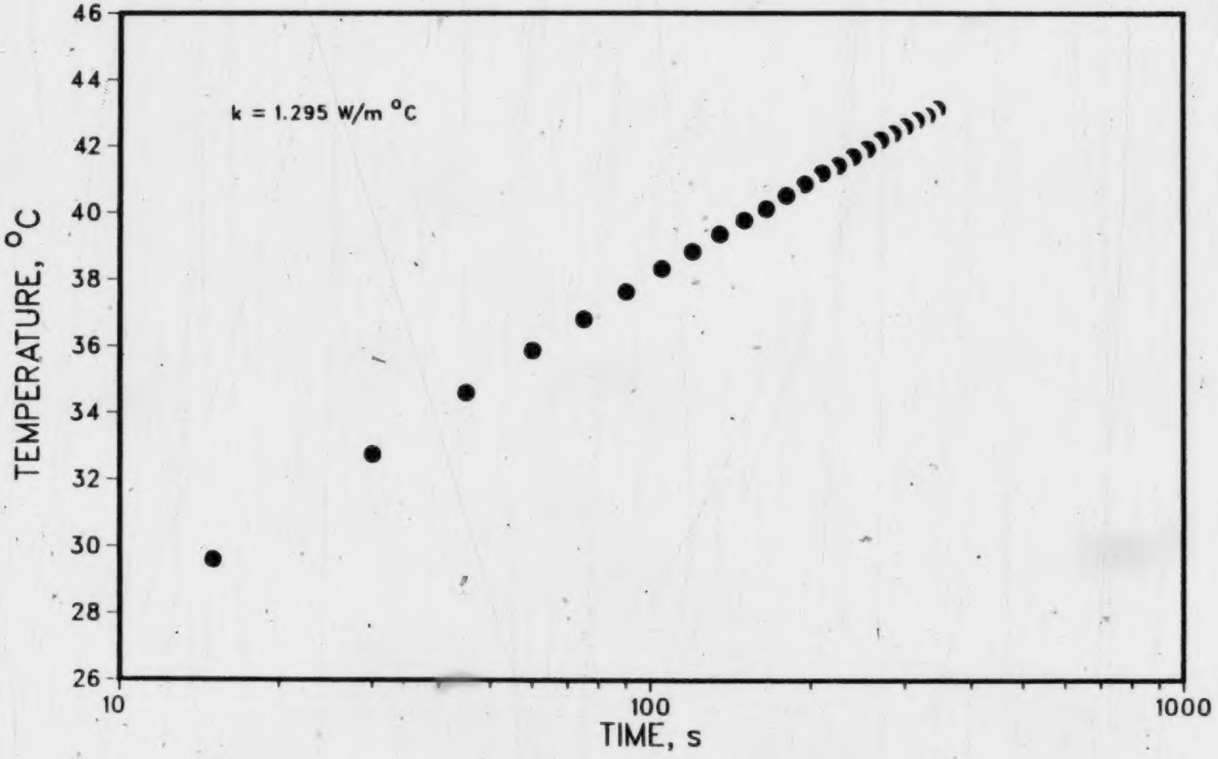


Figure F.2 Thermal Conductivity Test Data, ROSR-C21A

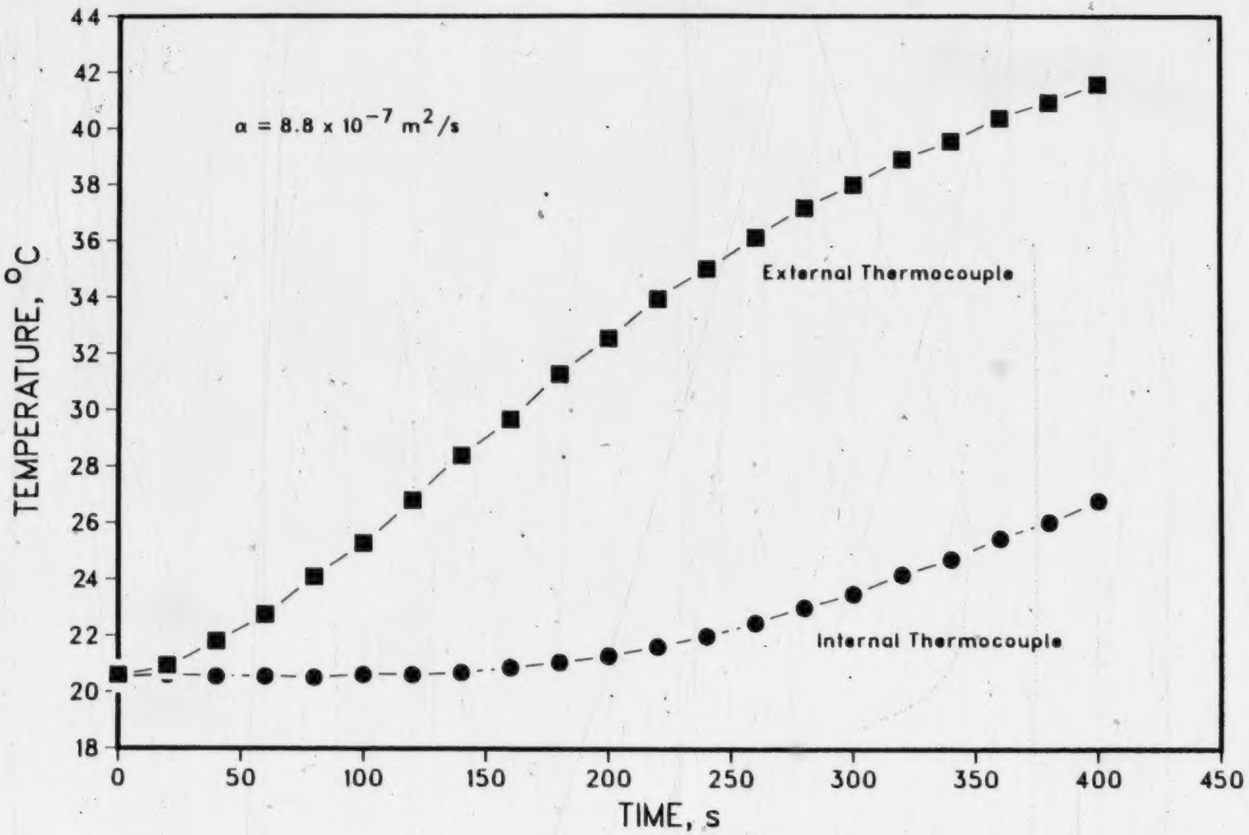


Figure F.3 Thermal Diffusivity Test Data, ROSR-D24A

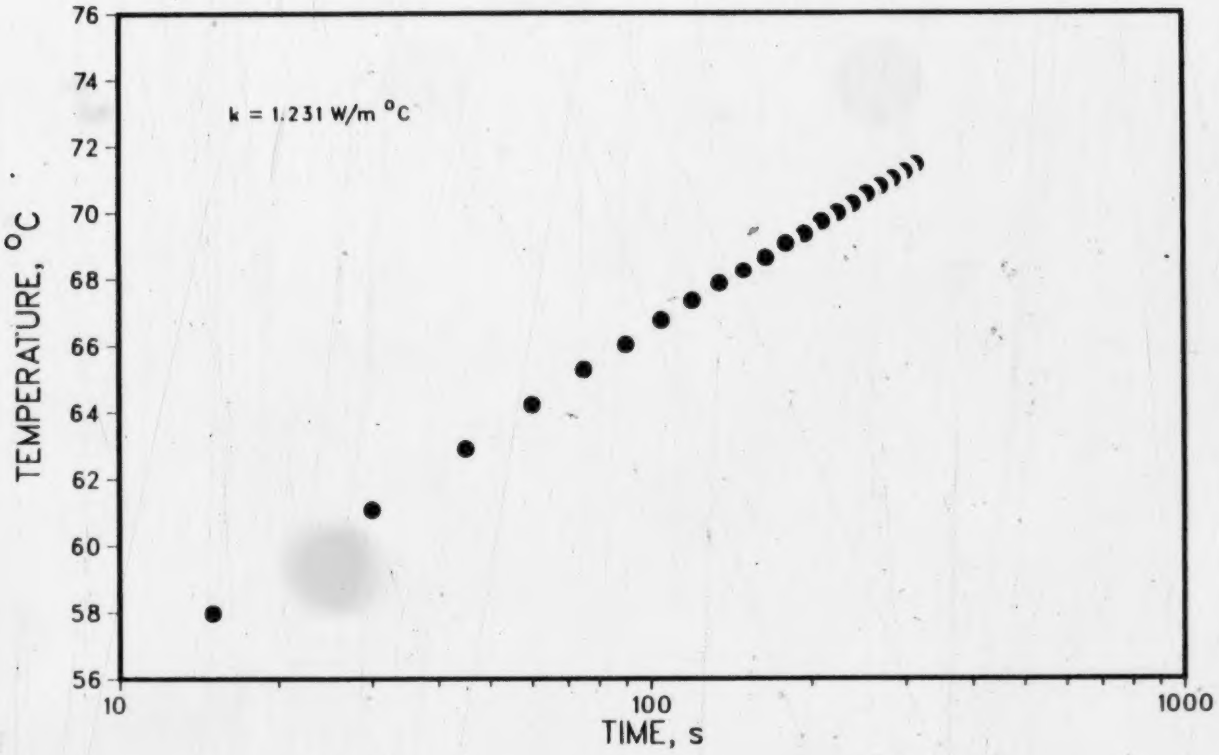


Figure F.4 Thermal Conductivity Test Data, ROSR-C49A

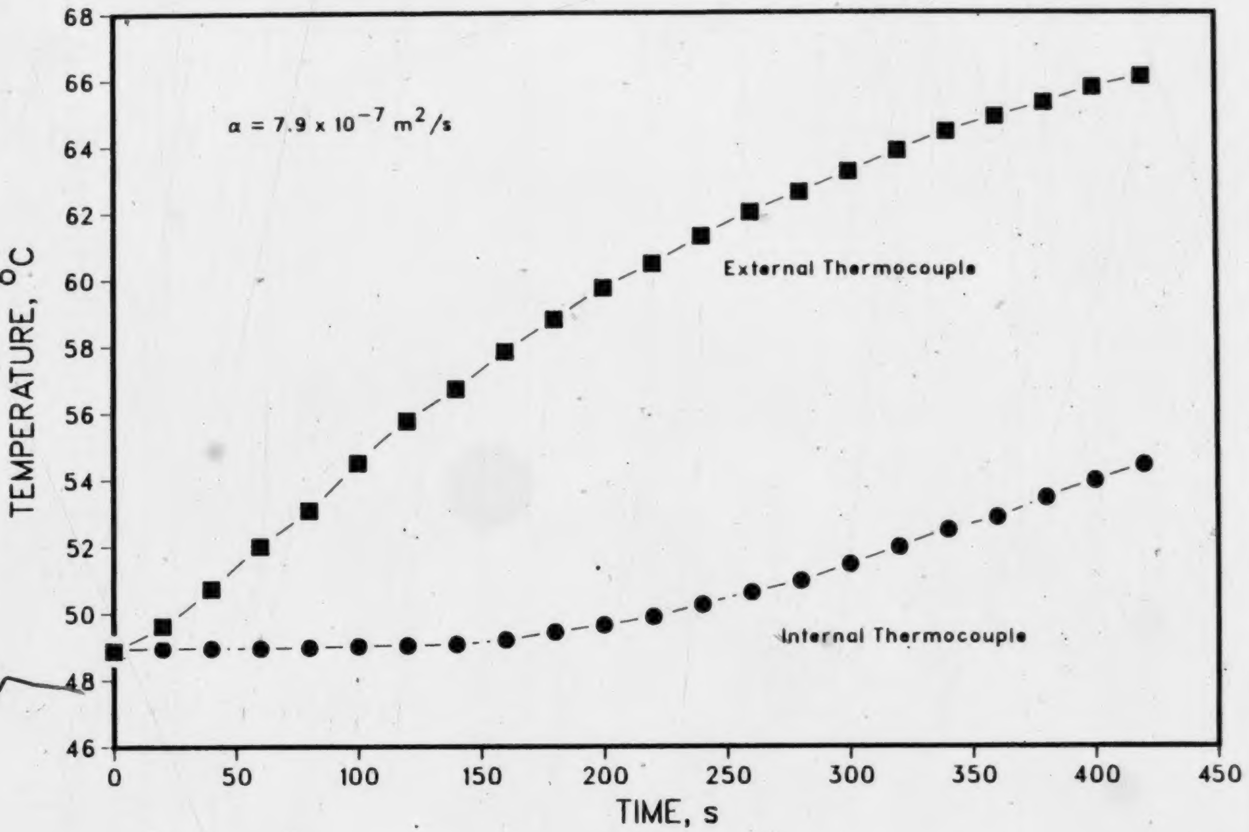


Figure F.5 Thermal Diffusivity Test Data, ROSR-D52A

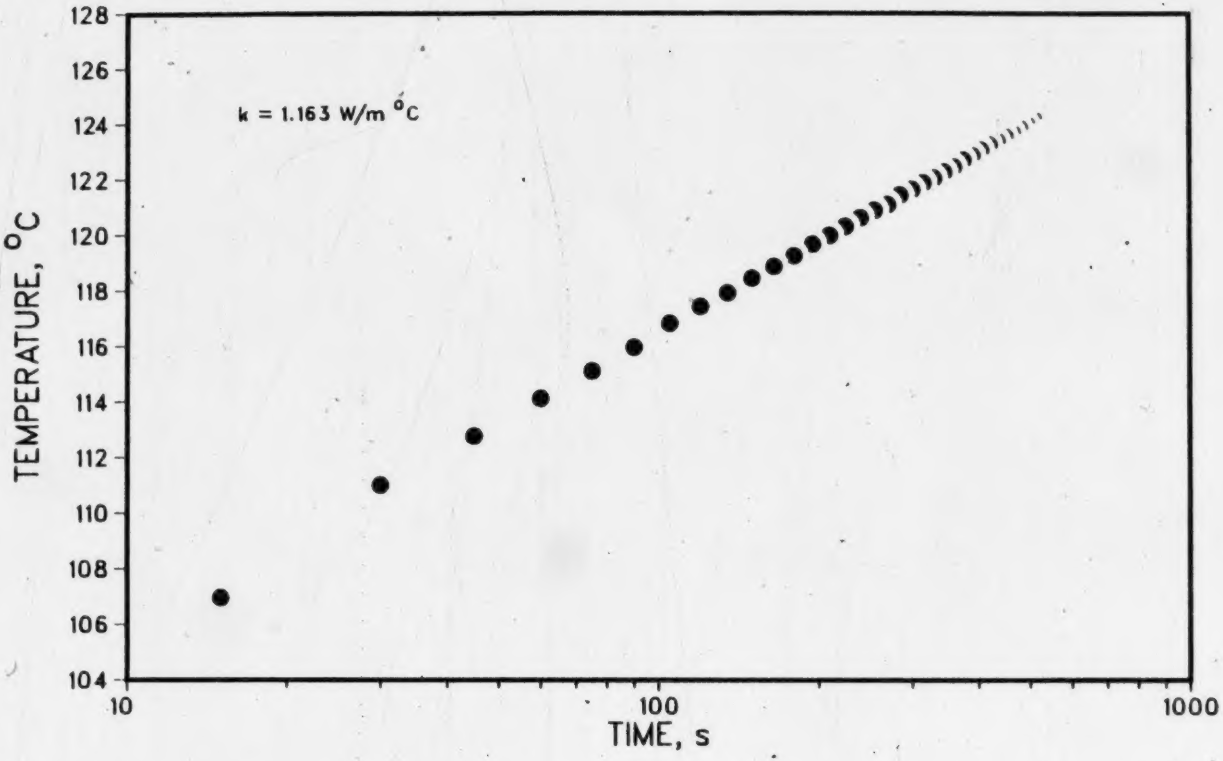


Figure F.6 Thermal Conductivity Test Data, ROSR-C99A

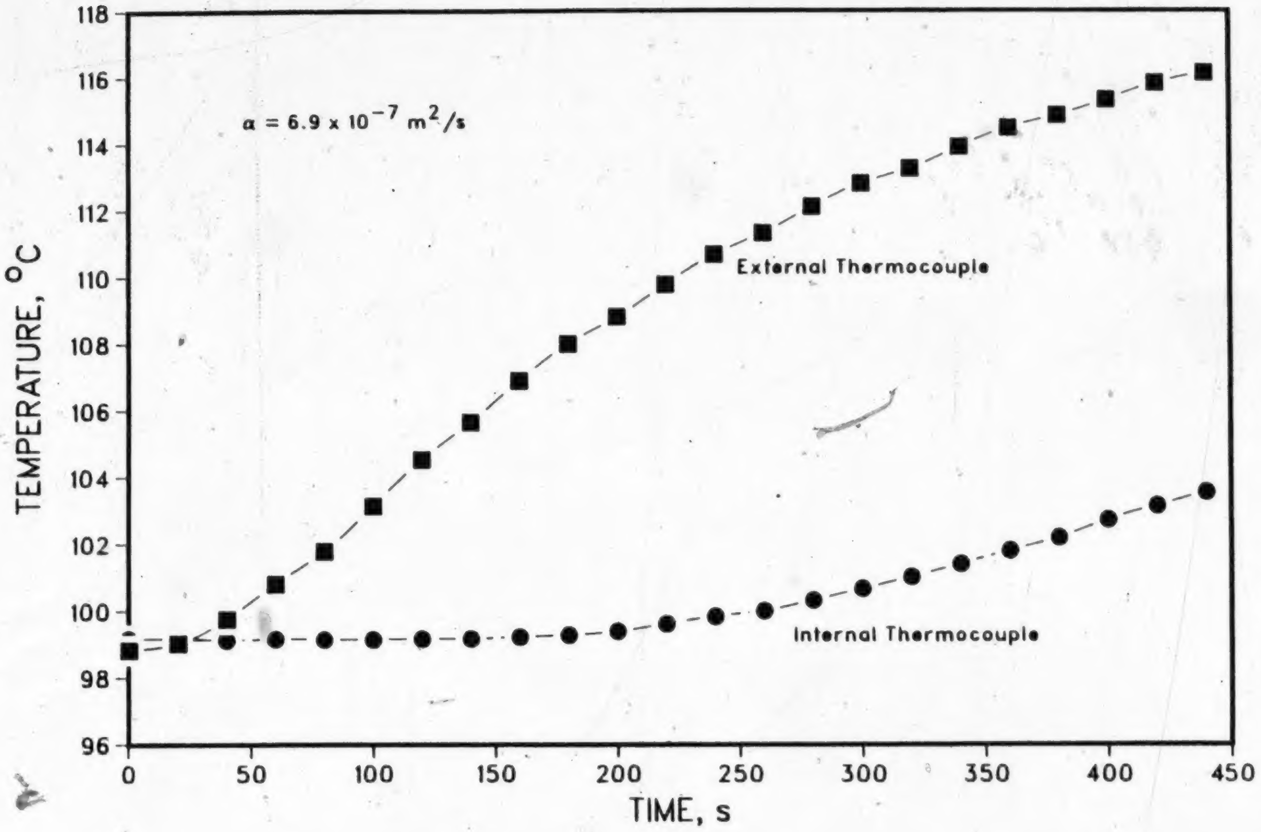


Figure F.7 Thermal Diffusivity Test Data, ROSR-D102A

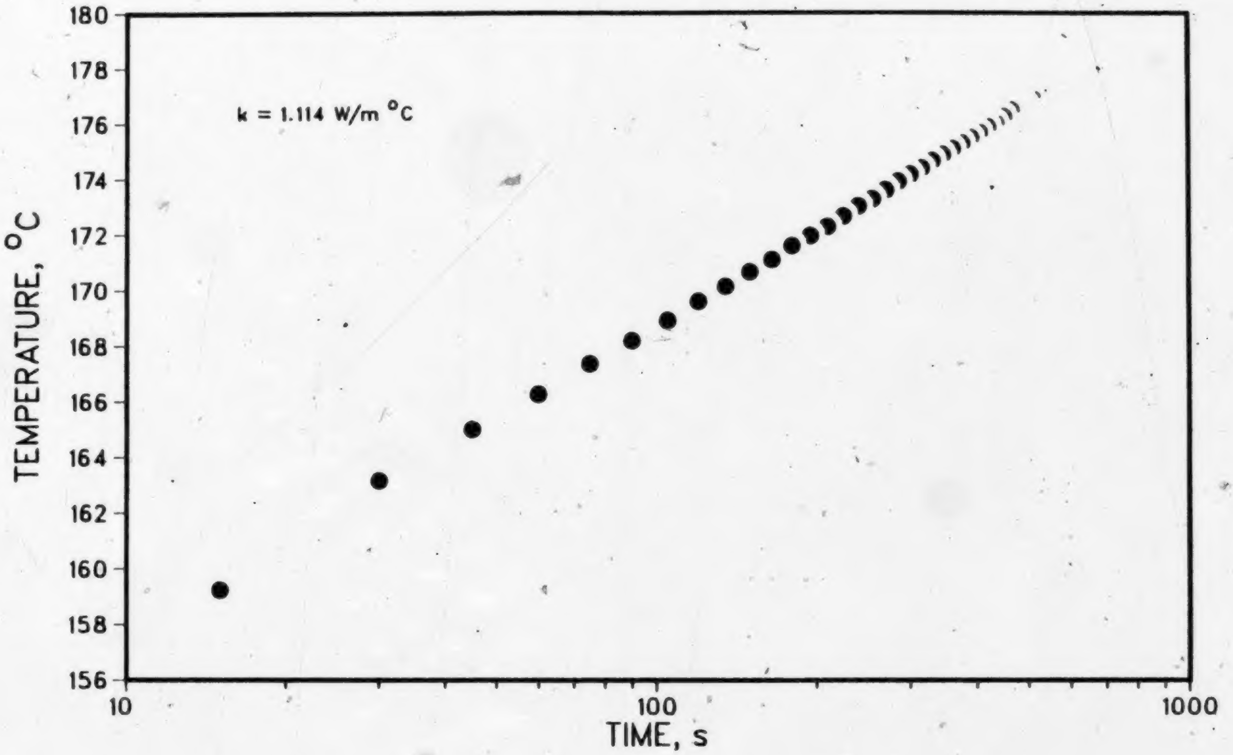


Figure F.8 Thermal Conductivity Test Data, ROSR-C151A

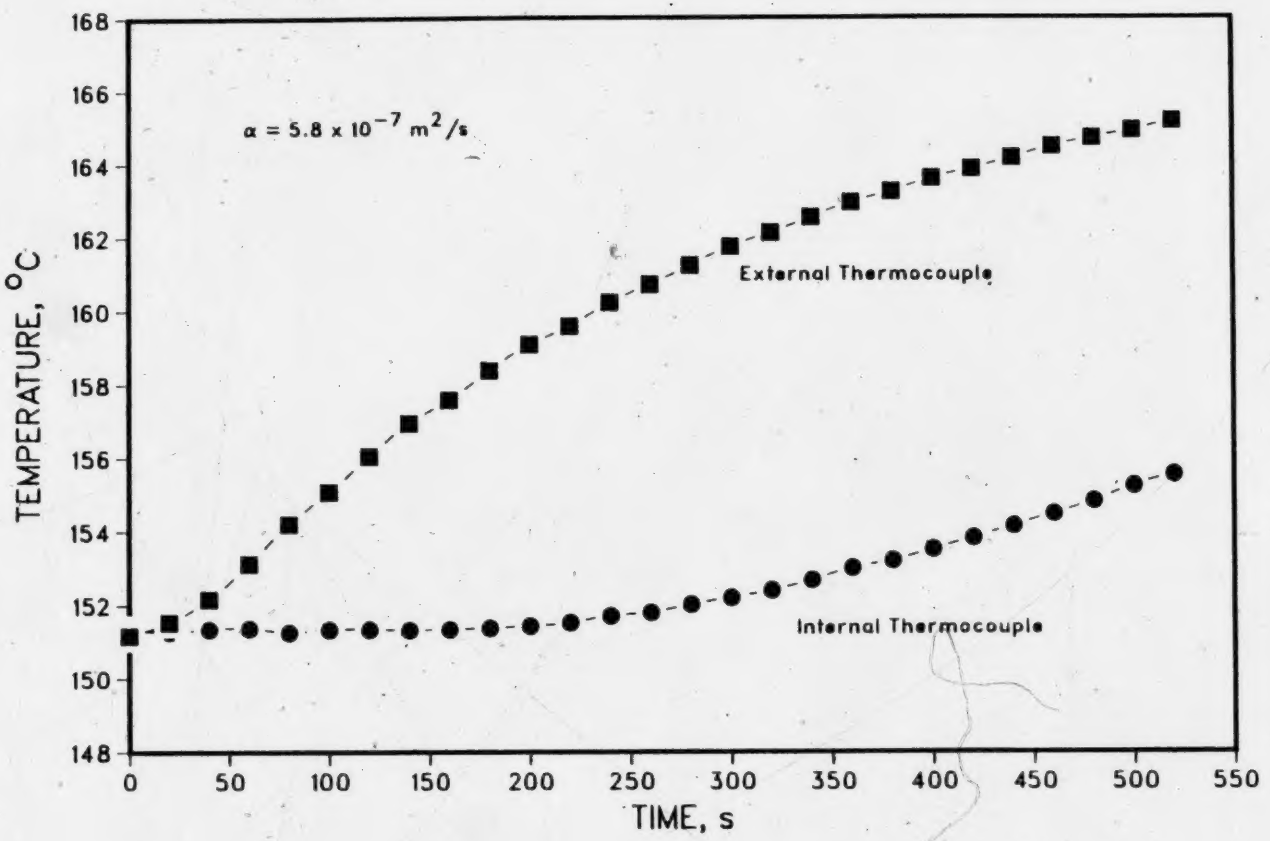


Figure F.9 Thermal Diffusivity Test Data, ROSR-D154A

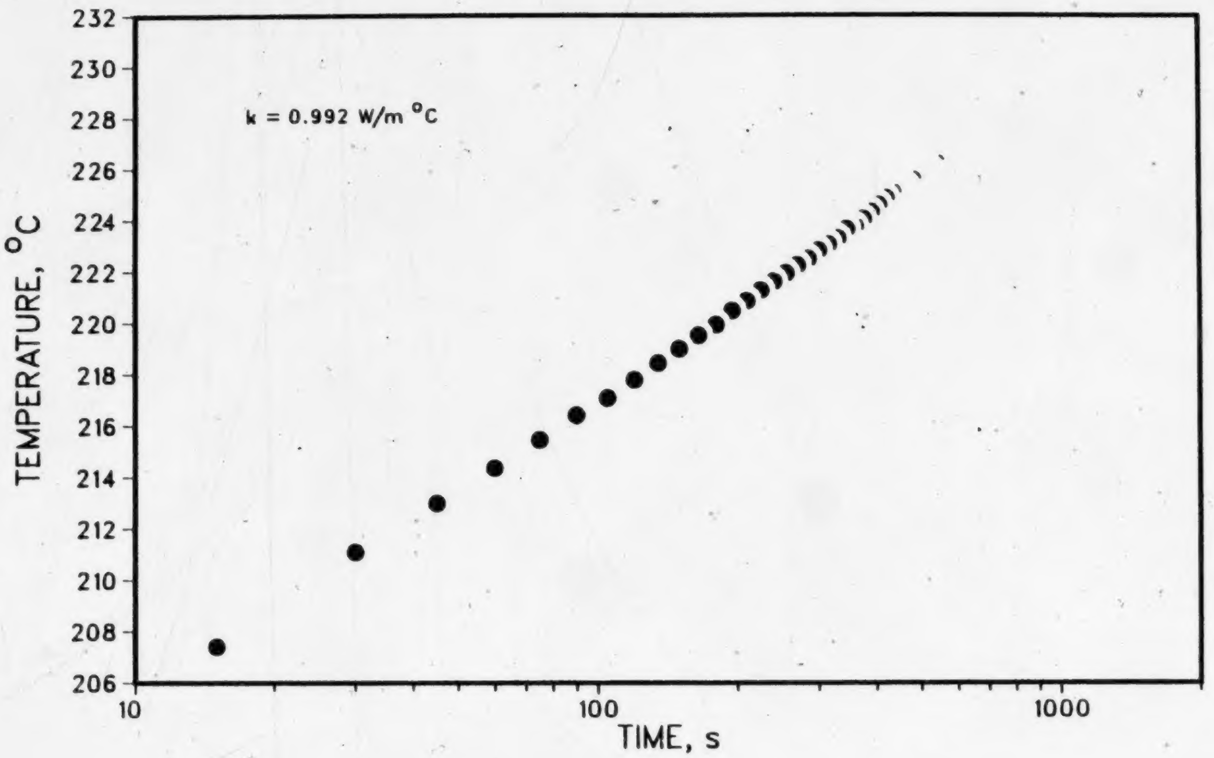


Figure F.10 Thermal Conductivity Test Data, ROSR-C199A

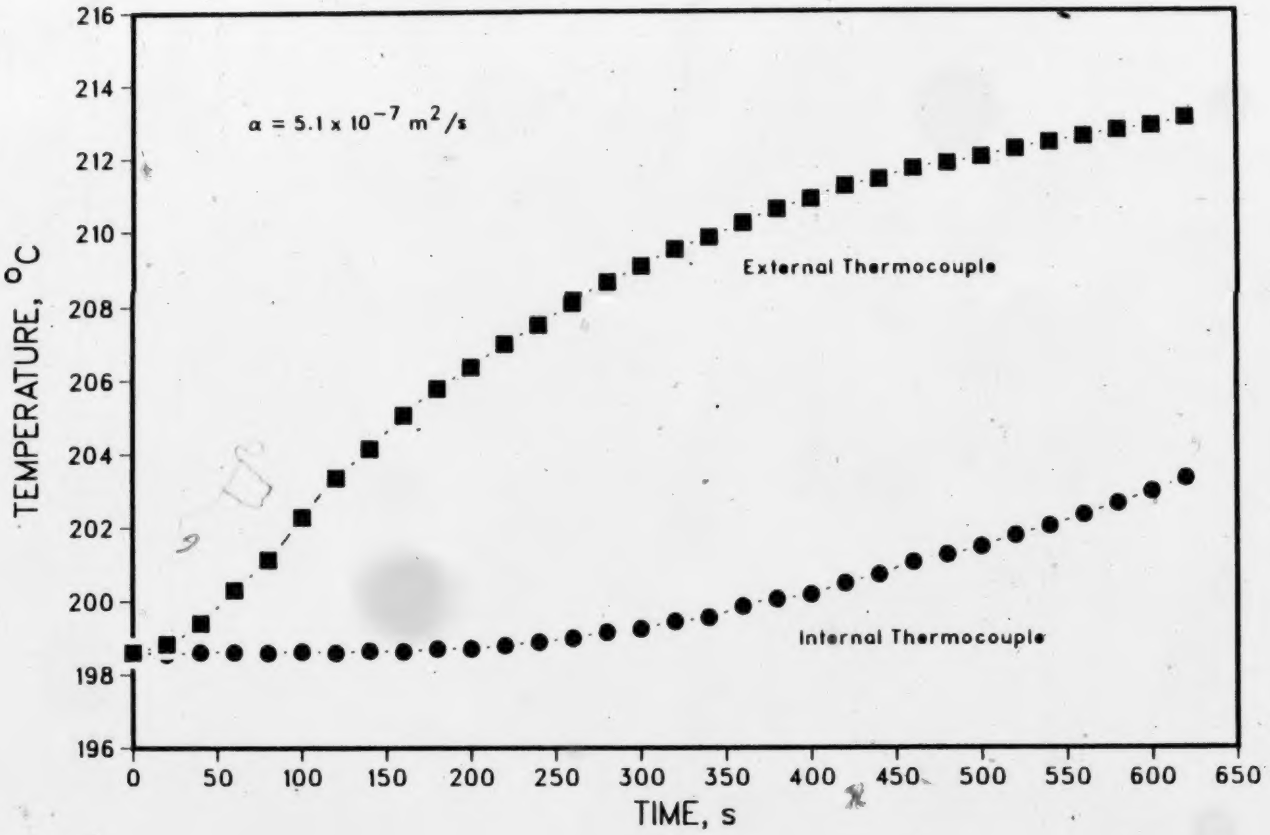


Figure F.11 Thermal Diffusivity Test Data, ROSR-D200A

APPENDIX G - Computer Programs and Sample Outputs

Program *CONDLR*

```
C
C  ***  TRANSIENT-STATE THERMAL CONDUCTIVITY TEST ***
C  ---  EVALUATION OF THE CONSTANTS A and B IN THE EQUATION:
C              T(t) = A * ln(t) + B
C       FROM A SET OF TIME-TEMPERATURE DATA
C       BY LEAST-SQUARES LINEAR REGRESSION METHOD
C
C  By:  Andrew Seto (July 17, 1984)
C       Department of Civil Engineering
C       University of Alberta
C       Edmonton, Alberta
C       CANADA   T6G  2G7
C
C
C  <<< Input Parameters >>>
C
C  TITLE    = Title of input data (80 characters)
C  VRES     = Voltage across the resistor, V.
C  VINP     = Voltage generated by power supply unit, V.
C  HCORE    = Height of test specimen, m.
C  RTC      = Radial distance of internal thermocouple from
C             central axis, m.
C  TO       = Time increment, s.
C  TEMPO    = Initial temperature of test specimen, deg C.
C  HLENG    = Heated length of thermal conductivity probe, m.
C  M        = Total number of temperature entries (time counter),
C             excluding initial temperature at time '0'.
C  NB       = Point at the time where the linear portion of the
C             temperature-ln t plot begins.
C             (e.g. NB=2 if the plot starts to become linear at
C                   the second time increment after start of test,
C                   i.e. when t=2*TO)
C  NE       = Point at the time where the linear portion of the
C             temperature-ln t plot ends.
C             (e.g. NE=10 if the plot ceases to be linear at
C                   the tenth time increment after start of test,
C                   i.e. when t=10*TO)
C  N(I)     = Number of time increments (1,2,3,4,5,..).
C  TEMP(I)  = Temperature at the corresponding time increment, deg C.
C  NDUMMY   = Dummy time increment input to be skipped.
C             The number of dummy input data depends on NB.
C  TDUMMY   = Dummy temperature input to be skipped.
C             The number of dummy input data depends on NB.
C  ( Ignore the dummy input data as the program will automatically
C    handle them according to the specified start time for analysis,
C    i.e. NB.   Simply enter time-temperature data according to the
C    time increment sequence of 1,2,3,4,5,... )
C
C
C
      DIMENSION TITLE(20),N(30),TEMP(30),TIME(30),TLOG(30)
      PI=3.1415927
      GAMMA=0.577216
      READ(5,1000) TITLE
      WRITE(6,2000) TITLE
      READ(5,1200) VRES,VINP,HCORE,RTC,TO,TEMPO,HLENG
      CRNT=VRES/2.
      POWER=(VINP-VRES)*CRNT
      Q=POWER/HLENG
      WRITE(6,2100) POWER,Q,HCORE,RTC,TO,TEMPO,HLENG
      READ(5,1300) M,NB,NE
      MM=NE-NB+1
      IF(MM.LE.1) GO TO 900
      RM=MM
      IB=NB-1
      IF(IB.LE.0) GO TO 20
      DO 10 I=1,IB
   10 READ(5,1400) NDUMMY,TDUMMY
   20 READ(5,1400) (N(I),TEMP(I),I=1,MM)
      DO 25 I=1,MM
      TEMP(I)=TEMP(I)-TEMPO
      TIME(I)=TO*FLOAT(N(I))
      TLOG(I)=ALOG(TIME(I))
   25 CONTINUE
      WRITE(6,2150)
      WRITE(6,2200)
      WRITE(6,2250) (TIME(I),TEMP(I),I=1,MM)
      SX=0.0
      SY=0.0
      SXY=0.0
      SX2=0.0
      SY2=0.0
      DO 50 I=1,MM
      SX=SX+TLOG(I)
      SY=SY+TEMP(I)
      SX2=SX2+TLOG(I)*TLOG(I)
      SY2=SY2+TEMP(I)*TEMP(I)
      SXY=SXY+TLOG(I)*TEMP(I)
   50 CONTINUE
      DEM=RM*SX2-SX*SX
      B=(SY*SX2-SX*SXY)/DEM
      A=(RM*SXY-SX*SY)/DEM
      SDX=SQRT(DEM/RM/(RM-1.))
      SDY=SQRT((SY2-SY*SY/RM)/(RM-1.))
      R=A*SDX/SDY
      WRITE(6,5000)
      WRITE(6,2200)
      DO 400 I=1,MM
      TEMT=A*TLOG(I)+B
      WRITE(6,2250) TIME(I),TEMT
  400 CONTINUE
      WRITE(6,3000)A,B,R
      XK=Q/(4.*PI*A)
      XK2=XK/1.73074
      XD=EXP(B/A+ALOG(RTC*RTC/4.)+GAMMA)
      WRITE(6,2600) XK,XK2,XD
      GO TO 999
  900 WRITE(6,4000)
  999 STOP
C
C  FORMAT STATEMENTS
C
 1000 FORMAT(20A4)
 1200 FORMAT(3F10.4,E16.6,F8.2,F15.4,F10.6)
 1300 FORMAT(3I4)
 1400 FORMAT(I4,F20.3)
 2000 FORMAT('1'/'0',9X,20A4)
 2100 FORMAT('0',9X,'POWER INPUT =',F10.3,' W (',F7.3,' W/m)'/
     *9X,' SAMPLE HEIGHT =',F11.5,' m'/
     *9X,' DISTANCE OF THERMOCOUPLE FROM CENTRE =',E16.6,' m'/
     *9X,' TIME INCREMENT =',F8.2,' seconds'/
     *9X,' INITIAL TEMPERATURE =',F10.3,' deg C'/
     *9X,' HEATED LENGTH OF PROBE =',F11.5,' m'//)
2150 FORMAT(//10X,'*** INPUT TIME-TEMPERATURE DATA ***')
2200 FORMAT(/10X,'TIME, t (sec)',10X,
     *'TEMP. RISE, T (C)'/
     *10X,13('*'),10X,17('*'))
2250 FORMAT(14X,F5.1,19X,F7.3)
2600 FORMAT(//10X,'THERMAL CONDUCTIVITY =',F10.4,' W/m*C   (',F7.4,
     *' BTU/(hr*ft*F) )'//10X,'THERMAL DIFFUSIVITY  =',E14.4,
     *' m**2/s'/10X,'( Assume negligible thermal ',
     *'contact resistance )')
3000 FORMAT(//10X,'GOVERNING EQUATION: ',5X,
     *'T(t) = A * ln(t) + B'/
     *10X,'A = ',F11.4/10X,'B = ',F11.4/
     *10X,'CORRELATION COEFFICIENT = ',F11.5)
4000 FORMAT(//10X,'*** ERROR ***'/10X,'AT LEAST TWO',
     *' PAIRS OF DATA POINTS ARE REQUIRED FOR THE ANALYSIS')
5000 FORMAT(///10X,'*** CALCULATED TEMPERATURES :',
     *'  BY LEAST-SQUARES LINEAR REGRESSION ***')
      END
End of file
```

```
THERM. COND. TEST No. C5003 (UOSL.C100W): March 15, 1985.

POWER INPUT =     10.587 W ( 71.292 W/m)
SAMPLE HEIGHT =    0.14650 m
DISTANCE OF THERMOCOUPLE FROM CENTRE =    0.158750E-02 m
TIME INCREMENT =   15.00 seconds
INITIAL TEMPERATURE =    99.404 deg C
HEATED LENGTH OF PROBE =    0.14850 m


*** INPUT TIME-TEMPERATURE DATA ***

TIME, t (sec)         TEMP. RISE, T (C)
*************         *****************
     30.0                   6.170
     45.0                   7.068
     60.0                   7.764
     75.0                   8.187
     90.0                   8.645
    105.0                   8.974
    120.0                   9.232
    135.0                   9.505


*** CALCULATED TEMPERATURES :  BY LEAST-SQUARES LINEAR REGRESSION ***

TIME, t (sec)         TEMP. RISE, T (C)
*************         *****************
     30.0                   6.182
     45.0                   7.081
     60.0                   7.719
     75.0                   8.213
     90.0                   8.618
    105.0                   8.959
    120.0                   9.255
    135.0                   9.516

GOVERNING EQUATION:       T(t) = A * ln(t) + B
A =        2.2166
B =       -1.3566
CORRELATION COEFFICIENT =     0.99972

THERMAL CONDUCTIVITY =     2.5595 W/m*C   ( 1.4788 BTU/(hr*ft*F) )

THERMAL DIFFUSIVITY  =     0.6085E-06 m**2/s
( Assume negligible thermal contact resistance )
```

Program *TDIFF*

```
C
C  *** PROGRAM TO EVALUATE THE THERMAL DIFFUSIVITY OF A MATERIAL
C      USING TEST DATA OBTAINED FROM A TRANSIENT STATE THERMAL
C      DIFFUSIVITY TEST.
C
C      By: Andrew Seto (March 18, 1985)
C          Dept. of Civil Engineering
C          University of Alberta
C          Edmonton, Alberta
C          CANADA  T6G 2G7
C
C
C  Run commands: $RUN *FORTG SCARDS=TDIFF SPUNCH=-T
C                $RUN -T 4=BJJ 5=datafile 6=outputfile
C
C
C  <<< Input Parameters >>>
C
C  -- UNIT #5 INPUT --
C  TITLE   = Title of input data.
C  N       = No. of time increments, including zero.
C  M       = No. of time increments for averaging initial
C            temperature of internal thermocouple,
C            including zero.
C  TO      = Time increment, s.
C  RO      = External sample radius, m.
C  R       = Radial distance of internal thermocouple from centre, m.
C  T52(I)  = Thermocouple #52 reading, deg. C. (I=1,2,3,...)
C  T53(I)  = Thermocouple #53 reading, deg. C. (I=1,2,3,...)
C  T55(I)  = Thermocouple #55 reading, deg. C. (I=1,2,3,...)
C  T56(I)  = Thermocouple #56 reading, deg. C. (I=1,2,3,...)
C  T57(I)  = Thermocouple #57 reading, deg. C. (I=1,2,3,...)
C
C
C  -- UNIT #4 INPUT --
C  BN(I), RJO(I), RJ1(I) are pre-defined functions which are
C            included in the file BJJ for input into unit #4.
C            RJO(I) and BJJ will have to be modified if RO changes.
C            The current BJJ file is valid for a test specimen with
C            diameter of 3 inches only.
C            To create a new RJO file (e.g. RJO2), and subsequently
C            a new BJJ file (e.g. BJJ2), the program JOPG may be used.
C
C
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION TITLE(20)
      DIMENSION T52(60),T53(60),T55(60),T56(60),T57(60)
      DIMENSION E1(60),E2(60),E3(60),E4(60),E5(60)
      DIMENSION E6(60),E7(60),X(7,7),Y(7),TX(7)
      COMMON TIME(60),TEMP(60),BN(56),AN(56),DN(56),RJ1(56)
      COMMON RJO(56),RO,R,A,B,C,D,E,F,G,H
C
      READ(5,1000) TITLE
      READ(5,1001) N,M,TO,RO,R
      DO 10 I=1,N
   10 READ(5,1003) T52(I),T53(I),T55(I),T56(I),T57(I)
C
C     * CALCULATE AVERAGE INITIAL TEMPERATURE (TEMPO)
C       (Internal thermocouple)
C
      SUM=0.0
      DO 20 I=1,M
   20 SUM=SUM+T52(I)
      RM=M
      TEMPO=SUM/RM
C
C     * CALCULATE AVERAGE TEMPERATURE OF THE OUTER THERMOCOUPLES
C
      DO 30 I=1,N
   30 TEMP(I)=(T55(I)+T57(I))/2.
C
      WRITE(6,1999) TITLE
      WRITE(6,2000) N,M
      WRITE(6,2001)TEMPO
      DO 40 I=1,N
      J=I-1
   40 WRITE(6,2002) J,TEMP(I)
C
C     FORMAT STATEMENTS
 1000 FORMAT(20A4)
 1001 FORMAT(2I5,3F20.7)
 1003 FORMAT(5G20.9)
 1999 FORMAT('1',9X,20A4)
 2000 FORMAT('0',9X,'Total Number of Scans = ',I5/
     *10X,'No. of Scans Used to Calculate TEMPO (Internal T.C.)',
     *' = ',I5/)
 2001 FORMAT(10X,'TEMPO = ',F10.3//
     *10X,'Average Temperature of Outer Thermocouples: '//
     *10X,'Time Increment',5X,'Temp. (C)'/10X,14('*'),5X,9('*')/)
 2002 FORMAT(15X,I4,11X,F7.3)
C
C  ***  MULTIPLE LINEAR REGRESSION  (METHOD OF LEAST-SQUARES)  ***
C  ---  Evaluation of the 8 constants in the polynomial :
C       T = AO + A1*E + A2*E**2 + A3*E**3 + ... + A7*E**7
C       from average temperature(T)-time(t) data
C       of the external thermocouples,
C       by Least-squares Multiple Linear Regression Method
C       (Gaussian Elimination Method is employed to solve
C        for the constants)
C
      DO 41 I=2,N
      TEMP(I)=TEMP(I)-TEMP(1)
   41 E1(I)=TO*FLOAT(I-1)
      TEMP(1)=0.0
      E1(1)=0.0
      DO 50 I=1,N
      EMF=E1(I)
      E2(I)=EMF*EMF
      E3(I)=EMF*E2(I)
      E4(I)=EMF*E3(I)
      E5(I)=EMF*E4(I)
      E6(I)=EMF*E5(I)
      E7(I)=EMF*E6(I)
   50 CONTINUE
      ST1=0.0
      ST2=0.0
      ST3=0.0
      ST4=0.0
      ST5=0.0
      ST6=0.0
      ST7=0.0
      STEMP=0.0
      DO 60 I=1,N
      ST1=ST1+E1(I)
      ST2=ST2+E2(I)
      ST3=ST3+E3(I)
      ST4=ST4+E4(I)
      ST5=ST5+E5(I)
      ST6=ST6+E6(I)
      ST7=ST7+E7(I)
      STEMP=STEMP+TEMP(I)
   60 CONTINUE
      RM=N
      AVE1=ST1/RM
      AVE2=ST2/RM
      AVE3=ST3/RM
      AVE4=ST4/RM
      AVE5=ST5/RM
      AVE6=ST6/RM
      AVE7=ST7/RM
      AVTEMP=STEMP/RM
      ALPHA=AVTEMP
      DO 70 I=1,7
      Y(I)=0.0
      DO 80 J=1,7
      X(I,J)=0.0
   80 CONTINUE
   70 CONTINUE
      STAVTQ=0.0
      DO 100 I=1,N
      TX(1)=E1(I)-AVE1
      TX(2)=E2(I)-AVE2
      TX(3)=E3(I)-AVE3
      TX(4)=E4(I)-AVE4
      TX(5)=E5(I)-AVE5
      TX(6)=E6(I)-AVE6
      TX(7)=E7(I)-AVE7
      TTX=TEMP(I)-AVTEMP
      DO 90 J=1,7
      Y(J)=Y(J)+TX(J)*TTX
      DO 110 K=1,7
      X(J,K)=X(J,K)+TX(J)*TX(K)
  110 CONTINUE
   90 CONTINUE
      STAVTQ=STAVTQ+TTX*TTX
  100 CONTINUE
      SDY2=STAVTQ/(RM-1.)
C
C  GAUSSIAN ELIMINATION TO FIND THE 7 CONSTANTS
C
C
C  Triangularization (Elimination)
C
      MK=6
      DO 120 NK=1,MK
      XX=X(NK,NK)
      IF(XX.EQ.0.) CALL EXIT
      L=NK+1
      DO 121 JK=L,7
      X(NK,JK)=X(NK,JK)/XX
  121 CONTINUE
      Y(NK)=Y(NK)/XX
      DO 120 IK=L,7
      DO 122 JK=L,7
      X(IK,JK)=X(IK,JK)-X(IK,NK)*X(NK,JK)
  122 CONTINUE
      Y(IK)=Y(IK)-X(IK,NK)*Y(NK)
  120 CONTINUE
C
C  Back Substitution
C
      Y(7)=Y(7)/X(7,7)
      DO 130 IK=1,MK
      NK=7-IK
      KKK=NK+1
      DO 131 JK=KKK,7
      Y(NK)=Y(NK)-X(NK,JK)*Y(JK)
  131 CONTINUE
  130 CONTINUE
      A=ALPHA-Y(1)*AVE1-Y(2)*AVE2-Y(3)*AVE3-Y(4)*AVE4-Y(5)*AVE5
      A=A-Y(6)*AVE6-Y(7)*AVE7
      B=Y(1)
      C=Y(2)
      D=Y(3)
      E=Y(4)
      F=Y(5)
      G=Y(6)
      H=Y(7)
      SUM=0.0
      DO 150 I=1,N
      TE1=E1(I)
      TE2=E2(I)
      TE3=E3(I)
      TE4=E4(I)
      TE5=E5(I)
      TE6=E6(I)
      TE7=E7(I)
      TEMT=A+Y(1)*TE1+Y(2)*TE2+Y(3)*TE3+Y(4)*TE4+Y(5)*TE5
      TEMT=TEMT+Y(6)*TE6+Y(7)*TE7
      SS=TEMP(I)-TEMT
      SUM=SUM+SS*SS
  150 CONTINUE
      RRM=RM-8.
      IF(RRM.LE.0.) GO TO 900
      SY2=SUM/(RRM)
      R2=1.-SY2/SDY2
      GO TO 999
  900 WRITE(6,4000)
      STOP
  999 CONTINUE
C
C  FORMAT STATEMENTS
C
 4000 FORMAT(//10X,'*** ERROR ***'/10X,'AT LEAST NINE',
     *' PAIRS OF DATA POINTS ARE REQUIRED FOR THE ANALYSIS')
C
C  PROGRAM TO EVALUATE THE THERMAL DIFFUSIVITY VALUE OF A MATERIAL
C  FROM A SET OF TIME-TEMPERATURE DATA BY REGULA-FALSI METHOD
C
```

```
      WRITE(6,1999) TITLE
      NB=M
      NE=N-1
      WRITE(6,2100) TO,TEMPO,RO,R,A,B,C,D,E,F,G,H
      WRITE(6,7000) R2
      READ(4,1200) (BN(I),I=1,56)
      READ(4,1200) (RJO(I),I=1,56)
      READ(4,1200) (RJ1(I),I=1,56)
      DO 5 I=1,56
      DN(I)=BN(I)/RO
    5 CONTINUE
      DO 200 I=NB,NE
      I2=I+1
      TIME(I)=E1(I2)
      TEMP(I)=T52(I2)-TEMPO
  200 CONTINUE
C
C  FIND ROOTS OF THE DIFFUSIVITY EQUATION BY REGULA-FALSI METHOD
C
      XLOW=1.
      XHIGH=100.
      DX=10.
      EPS=0.0001
      MAX=30
      NX=(XHIGH-XLOW)/DX+1.
      WRITE(6,2150)
      DO 250 II=NB,NE
      X1=XLOW-DX
      X2=XLOW
      DO 300 I=1,NX
      X1=X2
      X2=X2+DX
      CALL REGULA(X1,X2,EPS,MAX,II)
  300 CONTINUE
  250 CONTINUE
      STOP
C
C  FORMAT STATEMENTS
C
 1200 FORMAT(4E20.16)
 2100 FORMAT('O',9X,'TIME INCREMENT =',F6.2,' SECONDS'/
     *10X,'INITIAL TEMPERATURE =',F10.3,' DEG C'/
     *10X,'EXTERNAL SAMPLE RADIUS =',F9.6,' M'/
     *10X,'RADIAL DISTANCE OF T.C. FROM CENTRE =',F10.6,' M'/
     *10X,'A = ',E20.10/10X,'B = ',E20.10/
     *10X,'C = ',E20.10/10X,'D = ',E20.10/
     *10X,'E = ',E20.10/10X,'F = ',E20.10/
     *10X,'G = ',E20.10/10X,'H = ',E20.10/)
 2150 FORMAT(10X,'TIME (SEC)',5X,'TEMP. RISE (C)',5X,
     *'DIFF (*E-7 M**2/S)',5X,'ITERATES'/
     *10X,10('*'),5X,14('*'),5X,18('*'),5X,8('*'))
 7000 FORMAT(10X,'Reduction Coefficient (R**2) =',F10.4///)
      END
C
C  SUBROUTINE REGULA
C
      SUBROUTINE REGULA(XL,XH,EPS,MAX,II)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON TIME(60),TEMP(60),BN(56),AN(56),DN(56),RJ1(56)
      COMMON RJO(56),RO,R,A,B,C,D,E,F,G,H
      X1=XL
      X2=XH
      TM=TEMP(II)
      TTT=TIME(II)
      CALL YFUN(X1,Y1,II)
      CALL YFUN(X2,Y2,II)
      MX=O
      P=-1000.O
      IF(Y1*Y2.GT.O.O) RETURN
  600 IF(DABS(Y1-Y2).LT.1.OE-6) GO TO 800
      X3=(Y1*X2-Y2*X1)/(Y1-Y2)
      TEST=DABS(X3-P)
      IF(TEST.LT.EPS) GO TO 800
      CALL YFUN(X3,Y3,II)
      P=X3
      IF(Y1*Y3.GT.O.O) GO TO 650
      X2=X3
      Y2=Y3
      GO TO 700
  650 X1=X3
      Y1=Y3
  700 MX=MX+1
      IF(MX.LE.MAX) GO TO 600
      WRITE(6,2100) MAX
      GO TO 901
  800 WRITE(6,2200) TTT,TM,X3,MX
  901 RETURN
C
C  FORMAT STATEMENTS
C
 2100 FORMAT(10X,'*** PROGRAM HAS EXCEEDED',I3,' ITERATES')
 2200 FORMAT(12X,F6.2,11X,F6.3,14X,F8.4,13X,I2)
      END
C
C  SUBROUTINE YFUN
C
      SUBROUTINE YFUN(ALPHA,TT,II)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON TIME(60),TEMP(60),BN(56),AN(56),DN(56),RJ1(56)
      COMMON RJO(56),RO,R,A,B,C,D,E,F,G,H
      DO 45 KK=1,56
      AN(KK)=1.OE-7*ALPHA*DN(KK)*DN(KK)
   45 CONTINUE
      TM=TEMP(II)
      TTT=TIME(II)
      SUM=O.O
      DO 55 L=1,56
      ANN=AN(L)
      ANN2=ANN*ANN
      ANN3=ANN2*ANN
      ANN4=ANN2*ANN2
      ANN5=ANN3*ANN2
      ANN6=ANN3*ANN3
      TT1=B-2.*C/ANN+6.*D/ANN2-24.*E/ANN3+120.*F/ANN4-720.*G/ANN5
     *+5040.*H/ANN6
      TT2=(A-TT1/ANN)*(1.-DEXP(-1.*ANN*TTT))
      TT3=TTT*(TT1+TTT*((C-3.*D/ANN+12.*E/ANN2-60.*F/ANN3
     *+360.*G/ANN4-2520.*H/ANN5)+TTT*((D-4.*E/ANN+20.*F/ANN2
     *-120.*G/ANN3+840.*H/ANN4)+TTT*((E-5.*F/ANN+30.*G/ANN2
     *-210.*H/ANN3)+TTT*((F-6.*G/ANN+42.*H/ANN2)+TTT*((G-7.*H/ANN)
     *+H*TTT))))))
      TT4=TT2+TT3
      TT5=RJO(L)*TT4/(BN(L)*RJ1(L))
      SUM=SUM+TT5
   55 CONTINUE
      TT=2.*SUM-TM
      RETURN
      END
End of file
```

```
Thermal Diffusivity Test No. D5003 (UOSL.D100W): March 15, 1985

Total Number of Scans =     11
No. of Scans Used to Calculate TEMPO (Internal T.C.) =      4

TEMPO =      99.317

Average Temperature of Outer Thermocouples:

Time Increment      Temp. (C)
***************     *********

       0              98.750
       1              99.349
       2             100.701
       3             102.180
       4             103.567
       5             104.871
       6             105.980
       7             106.963
       8             107.881
       9             108.733
      10             109.456
```

```
Thermal Diffusivity Test No. D5003 (UOSL.D100W): March 15, 1985

TIME INCREMENT = 30.00 SECONDS
INITIAL TEMPERATURE =     99.317 DEG C
EXTERNAL SAMPLE RADIUS = 0.038100 M
RADIAL DISTANCE OF T.C. FROM CENTRE =  0.002381 M
A =     -0.2990995260E-03
B =     -0.5961085445E-02
C =      0.1202376533E-02
D =     -0.1354936500E-04
E =      0.8812678453E-07
F =     -0.3463811407E-09
G =      0.7473556886E-12
H =     -0.6713765765E-15

Reduction Coefficient (R**2) =     1.0000


TIME (SEC)        TEMP. RISE (C)       DIFF (*E-7 M**2/S)      ITERATES
***********       **************       ******************      ********
  120.00              0.163                 11.2488                8
  150.00              0.366                 11.3859                5
  180.00              0.624                 10.8827                3
  210.00              1.048                 10.9724                2
  240.00              1.582                 11.0478                2
  270.00              2.152                 10.9469                2
  300.00              2.813                 10.9627                2
```

Program *BNPG*

```
C
C  Program to evaluate roots of Jo(x)=0
C
C  By:    Andrew Seto
C         Dept. of Civil Engineering
C         University of Alberta
C         Edmonton, Alberta
C         T6G 2E0
C
C
      IMPLICIT REAL*8(A-H,O-Z)
      PI=3.1415926539
      WRITE(6,111) PI
  111 FORMAT(F20.16)
      DO 100 I=20,50
      A=4.*FLOAT(I)-1.
      PA=PI*A
      PA2=PA*PA
      PA4=PA2*PA2
      PA6=PA2*PA4
      PA8=PA4*PA4
      PA10=PA4*PA6
      S1=1.+2./PA2-62./(3.*PA4)+15116./(15.*PA6)-12554474./(105.*PA8)
     *+8368654292./(315.*PA10)
      S2=S1*PA/4.
      WRITE(6,1000) S2
 1000 FORMAT(F30.16)
  100 CONTINUE
      STOP
      END
End of file
```

Program *JOPG*

```
C
C  Program to evaluate Jo(r*Bn/Ro),
C    where r = radial distance of thermocouple from centre of sample
C          Ro= external radius of sample
C          Bn= roots of Jo(Bn)=0, n=1,2,3,...
C
C
C  r = 3/32 in   and   Ro = 1.5 in   are assumed in this program.
C  Therefore, r*Bn/Ro is the same as Bn/16.
C  If different r's and Ro's are used, the statement Z=BN(I)/16.,
C  within the #200 DO loop will have to be changed accordingly.
C
C
C  By:  Andrew Seto
C       Dept. of Civil Engineering
C       University of Alberta
C       Edmonton, Alberta
C       T6G  2G7
C
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION F(56),BN(56),XJO(56)
      READ(5,1000) (F(I),I=1,56)
 1000 FORMAT(2E30.16)
      READ(5,1100)(BN(I),I=1,56)
 1100 FORMAT(4F20.16)
      DO 200 I=1,56
      Z=BN(I)/16.
      IF (Z.GT.10.0) GO TO 905
      Z2=Z/2.
      RJO=1.0
      DO 600 LL=2,56
      NEXP=2*LL-2
      NP1=NEXP/2
      NP2=NEXP-NP1
      N1=LL-1
      IF((LL+1)/2-LL/2 .EQ. 0) GO TO 700
      RJO=RJO+(Z2**NP1/F(N1))*(Z2**NP2/F(N1))
      GO TO 600
  700 RJO=RJO-(Z2**NP1/F(N1))*(Z2**NP2/F(N1))
  600 CONTINUE
      GO TO 500
  905 Z3=3./Z
      Z32=Z3*Z3
      Z33=Z3*Z32
      Z34=Z32*Z32
      Z35=Z32*Z33
      Z36=Z33*Z33
      FO=.79788456-.00000077*Z3-.00552740*Z32-.00009512*Z33
     *+.00137237*Z34-.00072805*Z35+.00014476*Z36
      THETA=Z-.78539816-.04166397*Z3-.00003954*Z32+.00262573*Z33
     *-.00054125*Z34-.00029333*Z35+.00013558*Z36
      RJO=1./DSQRT(Z)*FO*DCOS(THETA)
  500 XJO(I)=RJO
  200 CONTINUE
      WRITE(6,2000) (XJO(I),I=1,56)
 2000 FORMAT(4F20.16)
      STOP
      END
End of file
```

Program *J1PG*

```
      C
      C  Program to evaluate J1(bn) where bn's are the roots of J0(bn)=0
      C
      C  By:  Andrew Seto (May 4, 1984)
      C       Dept. of Civil Engineering
      C       University of Alberta
      C       Edmonton, Alberta
      C       T6G  2G7
      C
            IMPLICIT REAL*8(A-H,O-Z)
            DIMENSION FACT(56),BN(56),RJ1(56)
            READ(4,1000) (BN(I),I=1,56)
            READ(5,1100) (FACT(I),I=1,56)
            DO 700 J=1,56
            W=BN(J)
            IF(W.GT.12.5) GO TO 905
            W2=W/2.
            RJ=W2
            DO 800 LL=2,56
            NEXP=2*LL-1
            NP1=NEXP/2
            NP2=NEXP-NP1
            N1=LL-1
            IF((LL+1)/2-LL/2.EQ.0) GO TO 900
            RJ=RJ+(W2**NP1/FACT(N1))*(W2**NP2/FACT(LL))
            GO TO 800
        900 RJ=RJ-(W2**NP1/FACT(N1))*(W2**NP2/FACT(LL))
        800 CONTINUE
            GO TO 910
        905 W3=3./W
            W32=W3*W3
            W33=W3*W32
            W34=W32*W32
            W35=W32*W33
            W36=W33*W33
            F1=.79788456+.00000156*W3+.01659667*W32+.00017105*W33
           *-.00249511*W34+.00113653*W35-.00020033*W36
            THETA=W-2.356194490+.12499612*W3+.00005650*W32-.00637879*W33
           *+.00074348*W34+.00079824*W35-.00029166*W36
            RJ=1./DSQRT(W)*F1*DCOS(THETA)
        910 RJ1(J)=RJ
        700 CONTINUE
            WRITE(6,2000) (RJ1(I),I=1,56)
            STOP
      C
      C  FORMAT STATEMENTS
      C
       1000 FORMAT(4F20.16)
       1100 FORMAT(2E30.16)
       2000 FORMAT(4F20.16)
            END
End of file
```

Program *FACTORIALPG*

```
C
C  PROGRAM TO EVALUATE FACTORIALS
C (FROM 1 TO 56)
C
C   Andrew Seto
C   Dept. of Civil Engineering
C   University of Alberta
C   Edmonton, Alberta
C   T6G  2G7
C
C
       IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION F(56)
      DO 200 K=1,56
      FACT=1
      DO 100 L=1,K
  100 FACT=FACT*FLOAT(L)
  200 F(K)=FACT
      WRITE (6,2000) (F(J),J=1,56)
      STOP
 2000 FORMAT(2E30.16)
      END
End of file
```

Data *BJJ*
(3 inch ø sample)

```
2.4048255577,5.5200781103,8.6537279129,11.7915344391,
14.9309177086,18.0710639679,21.2116366299,24.3524715308,
27.4934791320,30.6346064684,33.7758202136,36.9170986537,
40.0584257646,43.1997917132,46.3411883717,49.4826098974,
52.6240518411,55.7655107550,58.9069839261,62.0484691902,
65.18996480,68.33146933,71.47298160,74.61450064,
77.75602563,80.89755587,84.03909078,87.18062984,
90.32217264,93.46371878,96.60527950,99.74681968,
102.8883743,106.0299309,109.1714896,112.3130503,
115.4546127,118.5961766,121.7377421,124.8793089,
128.0208770,131.1624463,134.3040166,137.4455880,
140.5871604,143.7287336,146.8703076,150.0118825,
153.1534580,156.2950343,159.4366112,162.5781887,
165.7197667,168.8613454,172.0029245,175.1445041,
  0.9943603264225859  0.9704635484310310  0.9281944088625225  0.8687586774051697
  0.7938590319742084  0.7056330788367767  0.6065845092979501  0.4995034057005532
  0.3873778782720312  0.2732999086246684  0.1603685183476324  0.0515934702612944
 -0.0501973195651967 -0.1424436212864497 -0.2229291887952397 -0.2898460609533377
 -0.3418448336247453 -0.3780693586346715 -0.3981748648825075 -0.4023290671198983
 -0.3911964094187173 -0.3659061627532514 -0.3280056397030722 -0.2794002846237296
 -0.2222828298328425 -0.1590540589818956 -0.0922379796949265 -0.0243943713584992
  0.0419682744555725  0.1044764429936799  0.1609692950572105  0.2095664338128863
  0.2487276050117015  0.2772956472040779  0.2945282336691168  0.3001133772268736
  0.2941698210881116  0.2772323319156936  0.2502226541733427  0.2144073961171375
  0.1713445296378127  0.1228206013613281  0.0707810242181924  0.0172560360482246
 -0.0357149422387013 -0.0861578447194149 -0.1322347376673021 -0.1723083457717891
 -0.2049981117590214 -0.2292259253542703 -0.2442499983519392 -0.2496858729930450
 -0.2455140477720318 -0.2320740023758598 -0.2100452601081429 -0.1804162189237283
  0.5191474972885542 -0.3402648065575249  0.2714522999287373 -0.2324598313630077
  0.2065464157097292 -0.1877287894229634  0.1732658836410648 -0.1617015424345353
  0.1521812072757352 -0.1441659725078224  0.1372969392139169 -0.1313246232116025
  0.1260694942249487 -0.1213986222875715  0.1172111967228329 -0.1134291906883523
  0.1099911412998103 -0.1068478866455850  0.1039595713636258 -0.1012934975057000
  0.0988225524305315 -0.0965240391352305  0.0943787926898292 -0.0923705035488153
  0.0904851928970749 -0.0887108011832216  0.0870368620649044 -0.0854542416580804
  0.0839549280215193 -0.0825318600458104  0.0811787773379888 -0.0798901531740034
  0.0786610003983566 -0.0774868897572176  0.0763638319498460 -0.0752882312267463
  0.0742568368312868 -0.0732667013952426  0.0723151453564780 -0.0713997268565921
  0.0705182149212287 -0.0696685668135333  0.0688489080955552 -0.0680575150135278
  0.0672927995070392 -0.0665532957338112  0.0658376481030383 -0.0651446008782481
  0.0644729891241968 -0.0638217300733357  0.0631898161720227 -0.0625763082672515
  0.0619803298598085 -0.0614010616861605  0.0608377372810133 -0.0602896383764433
End of file
```

Program *AVGTEMP*

```
C
C  A PROGRAM TO EVALUATE THE RADIAL TEMPERATURE DISTRIBUTION
C  AND THE AVERAGE TEMPERATURE OF A CYLINDRICAL SAMPLE DURING
C  A TRANSIENT-STATE THERMAL CONDUCTIVITY TEST
C  (TIME = 100 SECONDS)
C  (DISTANCE FROM CENTRAL AXIS OF SYMMETRY:  0.0625 TO 1.50 IN)
C
C  BY:  ANDREW SETO (DEC. 30, 1983)
C         DEPARTMENT OF CIVIL ENGINEERING
C         UNIVERSITY OF ALBERTA
C         EDMONTON, ALBERTA, CANADA
C
      DIMENSION R(100),F(56),T(100)
      C=0.5772156649
      PI=3.141592654
C
      READ (4,1001) (F(JJ),JJ=1,56)
   10 READ (5,1000) NT,Q,XK,XD,TEMPO
      IF (NT.EQ.0) GO TO 999
      WRITE (6,2000) NT,Q,XK,XD,TEMPO
      SLOPE=Q/(4.*PI*XK)
      DENOM=4.*100.*XD
      DO 200 JJJ=1,83
      T(JJJ)=0.0
  200 CONTINUE
      DO 300 I=1,37
      R(I)=0.0546875+FLOAT(I)/128.
  300 CONTINUE
      DO 400 J=38,55
      R(J)=0.015625*FLOAT(J)-0.234375
  400 CONTINUE
      DO 500 M=56,83
      R(M)=0.03125*FLOAT(M)-1.08375
  500 CONTINUE
      WRITE (6,2100)
      DO 600 N=1,83
      RX=0.0254*R(N)
      Y=RX**2/DENOM
      X=-1.*Y
      CALL TEMP(N,Y,X,C,SLOPE,F,T)
      WRITE (6,2200) R(N),T(N)
  600 CONTINUE
      SUMTA=0.0
      DO 700 IB=1,82
      TAVE=(T(IB)+T(IB+1))/2.0
      TAREA=R(IB+1)**2-R(IB)**2
      SUMTA=SUMTA+TAVE*TAREA
  700 CONTINUE
      AREA=R(83)**2-R(1)**2
      ATEMP=SUMTA/AREA+TEMPO
      WRITE (6,2300) ATEMP
      GO TO 10
  999 STOP
C
C  FORMAT STATEMENTS
C
 1000 FORMAT(I4,2F16.6,E16.6,F16.6)
 1001 FORMAT(2E30.16)
 2000 FORMAT('1','    THERMAL CONDUCTIVITY TEST NO.',I4/
     *'     POWER INPUT =',F10.3,' W/M'/
     *'     THERMAL CONDUCTIVITY =',F10.4,' W/(M*C)'/
     *'     THERAML DIFFUSIVITY =',E14.4,' (M**2)/S'/
     *'     INITIAL TEMPERATURE =',F10.3,' DEG. C'///)
 2100 FORMAT('     *** RADIAL TEMPERATURE DISTRIBUTION ***'/
     *'     (RADIUS MEASURED FROM AXIS OF SYMMETRY)'//
     *10X,'RADIUS (IN)',10X,'TEMPERATURE CHANGE (C)'/
     *10X,11('*'),10X,22('*')/)
 2200 FORMAT(11X,F9.7,16X,F11.7)
 2300 FORMAT(//'     AVERAGE TEMPERATURE =',F10.3)
      END
C
C  SUBROUTINE TEMP
C
      SUBROUTINE TEMP(NN,YY,XX,CC,SLOPE2,FF,TT)
      DIMENSION FF(56),TT(100)
      SUM=0.0
      IF (YY.GT.9) GO TO 30
      E=CC+ALOG(YY)
      DO 20 MM=1,56
      SUM=SUM+(XX**MM/FLOAT(MM))/FF(MM)
   20 CONTINUE
      E=E+SUM
      TT(NN)=-1.*E*SLOPE2
      GO TO 40
   30 TT(NN)=0.0
   40 RETURN
      END
End of file
```

```
THERMAL CONDUCTIVITY TEST NO.    1
POWER INPUT =     84.381 W/M
THERMAL CONDUCTIVITY =     2.0730 W/(M*C)
THERAML DIFFUSIVITY =    0.3703E-06 (M**2)/S
INITIAL TEMPERATURE =    98.054 DEG. C


*** RADIAL TEMPERATURE DISTRIBUTION ***
(RADIUS MEASURED FROM AXIS OF SYMMETRY)

       RADIUS (IN)          TEMPERATURE CHANGE (C)
       ***********          **********************

        0.0625000                  11.3806362
        0.0703125                  10.6320915
        0.0781250                   9.9656963
        0.0859375                   9.3660593
        0.0937500                   8.8218298
        0.1015625                   8.3243694
        0.1093750                   7.8669691
        0.1171875                   7.4442930
        0.1250000                   7.0520477
        0.1328125                   6.6867123
        0.1406250                   6.3453636
        0.1484375                   6.0255527
        0.1562500                   5.7251968
        0.1640625                   5.4425268
        0.1718750                   5.1759911
        0.1796875                   4.9242706
        0.1875000                   4.6861973
        0.1953125                   4.4607344
        0.2031250                   4.2469797
        0.2109375                   4.0441170
        0.2187500                   3.8514166
        0.2265625                   3.6682281
        0.2343750                   3.4939585
        0.2421875                   3.3280697
        0.2500000                   3.1700745
        0.2578125                   3.0195265
        0.2656250                   2.8760090
        0.2734375                   2.7391539
        0.2812500                   2.6086025
        0.2890625                   2.4840336
        0.2968750                   2.3651562
        0.3046875                   2.2516775
        0.3125000                   2.1433420
        0.3203125                   2.0399065
        0.3281250                   1.9411383
        0.3359375                   1.8468246
        0.3437500                   1.7567635
        0.3593750                   1.5886364
        0.3750000                   1.4353504
        0.3906250                   1.2956381
        0.4062500                   1.1683540
        0.4218750                   1.0524626
        0.4375000                   0.9470184
        0.4531250                   0.8511542
        0.4687500                   0.7640802
        0.4843750                   0.6850675
```

```
          0.5000000                  0.6134413
          0.5156250                  0.5485867
          0.5312500                  0.4899327
          0.5468750                  0.4369495
          0.5625000                  0.3891438
          0.5781250                  0.3460829
          0.5937500                  0.3073433
          0.6093750                  0.2725381
          0.6250000                  0.2413132
          0.6562500                  0.1883224
          0.6875000                  0.1460631
          0.7187500                  0.1125585
          0.7500000                  0.0861897
          0.7812500                  0.0655605
          0.8125000                  0.0495310
          0.8437500                  0.0371653
          0.8750000                  0.0277064
          0.9062500                  0.0205025
          0.9375000                  0.0150595
          0.9687500                  0.0110096
          1.0000000                  0.0079545
          1.0312500                  0.0057334
          1.0625000                  0.0040869
          1.0937500                  0.0028945
          1.1250000                  0.0020357
          1.1562500                  0.0014210
          1.1875000                  0.0009731
          1.2187500                  0.0006734
          1.2500000                  0.0003583
          1.2812500                  0.0002626
          1.3125000                  0.0000185
          1.3437500                  0.0000031
          1.3750000                 -0.0000278
          1.4062500                 -0.0001514
          1.4375000                  0.0
          1.4687500                  0.0
          1.5000000                  0.0

AVERAGE TEMPERATURE =     98.360
```

Program *AVGTEMPD*

```
C
C  PROGRAM TO EVALUATE THE RADIAL TEMPERATURE DISTRIBUTION
C  AND THE AVERAGE TEMPERATURE OF A CYLINDRICAL SAMPLE DURING
C  A TRANSIENT-STATE THERMAL DIFFUSIVITY TEST
C  (TIME = 120 SECONDS)
C  (DISTANCE FROM CENTRAL AXIS OF SYMMETRY:  0.125 TO 1.50 in)
C
C  BY:  ANDREW SETO (Jan. 15, 1985)
C       DEPT. OF CIVIL ENGINEERING
C       UNIVERSITY OF ALBERTA
C       EDMONTON,  ALBERTA
C       T6G  2G7
C
C
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BN(56),AN(56),DN(56),RJ1(56)
      COMMON RJO(81,56),TEMP(81),R(81),A,B,C,D,E,F,G,H
      DIMENSION TITLE(20)
      RO=0.0381
C
C  INPUT DATA
C
      READ(5,1000) TITLE
      WRITE(6,2000) TITLE
      READ(5,1100) XD,TEMPO
      READ(5,1200) A,B,C,D
      READ(5,1200) E,F,G,H
      WRITE(6,2100) XD,TEMPO,A,B,C,D,E,F,G,H
      READ(4,1200) (BN(I),I=1,56)
      READ(4,1200) (RJ1(I),I=1,56)
      DO 5 K=1,81
      READ(4,1400) R(K)
 1400 FORMAT(F20.16)
      READ(4,1450) (RJO(K,I),I=1,56)
 1450 FORMAT(4F20.16)
    5 CONTINUE
      DO 6 I=1,56
      DN(I)=BN(I)/RO
      AN(I)=XD*DN(I)**2
    6 CONTINUE
      WRITE(6,2150)
      DO 10 II=1,81
      CALL TEM(II)
      WRITE(6,2200) R(II),TEMP(II)
   10 CONTINUE
      SUMTA=0.0
      DO 700 IB=1,80
      TAVE=(TEMP(IB)+TEMP(IB+1))/2.0
      TAREA=R(IB)**2-R(IB+1)**2
      SUMTA=SUMTA+TAVE*TAREA
  700 CONTINUE
      AREA=R(1)**2-R(81)**2
      ATEMP=SUMTA/AREA+TEMPO
      WRITE(6,2300) ATEMP
      STOP
C
C  FORMAT STATEMENTS
C
 1000 FORMAT(20A4)
 2000 FORMAT('1',9X,20A4)
 1100 FORMAT(2F20.4)
 1200 FORMAT(4E20.16)
 2100 FORMAT('0',9X,
     *'THERMAL DIFFUSIVITY =',E11.4,' m**2/s'/
     *10X,'INITIAL TEMPERATURE =',F10.3,' Deg C'/
     *10X,'A = ',E20.10/10X,'B = ',E20.10/
     *10X,'C = ',E20.10/10X,'D = ',E20.10/
     *10X,'E = ',E20.10/10X,'F = ',E20.10/
     *10X,'G = ',E20.10/10X,'H = ',E20.10///)
 2150 FORMAT('    *** RADIAL TEMPERATURE DISTRIBUTION ***'/
     *'     (RADIUS MEASURED FROM AXIS OF SYMMETRY)'//
     *10X,'RADIUS (IN)',10X,'TEMPERATURE CHANGE (C)'/
     *10X,11('*'),10X,22('*')/)
 2200 FORMAT(11X,F9.7,16X,F11.7)
 2300 FORMAT(//'    AVERAGE TEMPERATURE =',F10.3)
      END
C
C  SUBROUTINE TEM
C
      SUBROUTINE TEM(II)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BN(56),AN(56),FACT(56),DN(56),RJ1(56)
      COMMON RJO(81,56),TEMP(81),R(81),A,B,C,D,E,F,G,H
      TTT=120.
      SUM=0.0
      DO 50 L=1,56
      ANN=AN(L)
      ANN2=ANN*ANN
      ANN3=ANN2*ANN
      ANN4=ANN2*ANN2
      ANN5=ANN3*ANN2
      ANN6=ANN3*ANN3
      TT1=B-2.*C/ANN+6.*D/ANN2-24.*E/ANN3+120.*F/ANN4-720.*G/ANN5
     *+5040.*H/ANN6
      TT2=(A-TT1/ANN)*(1.-DEXP(-1.*ANN*TTT))
      TT3=TTT*(TT1+TTT*((C-3.*D/ANN+12.*E/ANN2-60.*F/ANN3
     *+360.*G/ANN4-2520.*H/ANN5)+TTT*((D-4.*E/ANN+20.*F/ANN2
     *-120.*G/ANN3+840.*H/ANN4)+TTT*((E-5.*F/ANN+30.*G/ANN2
     *-210.*H/ANN3)+TTT*((F-6.*G/ANN+42.*H/ANN2)+TTT*((G-7.*H/ANN)
     *+H*TTT)))))
      TT4=TT2+TT3
      TT5=RJO(II,L)*TT4/(BN(L)*RJ1(L))
      SUM=SUM+TT5
   50 CONTINUE
      TEMP(II)=2.*SUM
      RETURN
      END
End of file
```

```
          Average Sample Temperature Calculations

          THERMAL DIFFUSIVITY = 0.5000E-06 m**2/s
          INITIAL TEMPERATURE =     0.0   Deg C
          A =      0.0
          B =      0.6000000000E-01
          C =      0.0
          D =      0.0
          E =      0.0
          F =      0.0
          G =      0.0
          H =      0.0


*** RADIAL TEMPERATURE DISTRIBUTION ***
(RADIUS MEASURED FROM AXIS OF SYMMETRY)

          RADIUS (IN)           TEMPERATURE CHANGE (C)
          ***********           **********************

           1.4999990                  0.0004875
           1.4921865                  3.8320179
           1.4843740                  6.6319015
           1.4765615                  7.8352406
           1.4687490                  7.5883865
           1.4609365                  6.5871130
           1.4531240                  5.6459288
           1.4453115                  5.2661451
           1.4374990                  5.4480930
           1.4296865                  5.8221963
           1.4218740                  5.9722080
           1.4140615                  5.7219895
           1.4062490                  5.2111307
           1.3984365                  4.7446080
           1.3906240                  4.5521343
           1.3828115                  4.6350377
           1.3749990                  4.7955279
           1.3671865                  4.8047931
           1.3593740                  4.5737296
           1.3515615                  4.2032297
           1.3437490                  3.8902126
           1.3359365                  3.7722428
           1.3281240                  3.8304845
           1.3203115                  3.9173264
           1.3124990                  3.8776320
           1.3046865                  3.6659097
           1.2968740                  3.3723197
           1.2890615                  3.1447939
           1.2812490                  3.0730595
           1.2734365                  3.1244012
           1.2656240                  3.1762363
           1.2578115                  3.1148292
           1.2499990                  2.9214200
           1.2421865                  2.6811548
           1.2343740                  2.5123405
           1.2265615                  2.4741529
           1.2187490                  2.5242638
           1.2031250                  2.4842015
           1.1875000                  2.1090269
```

```
       1.1718750                  1.9725774
       1.1562500                  2.0420212
       1.1406250                  1.8041455
       1.1250000                  1.5510812
       1.1093750                  1.6100550
       1.0937500                  1.5390313
       1.0781250                  1.2578671
       1.0625000                  1.2235647
       1.0468750                  1.2748471
       1.0312500                  1.0612975
       1.0156250                  0.9174223
       1.0000000                  1.0028985
       0.9843750                  0.9141793
       0.9687500                  0.7078879
       0.9531250                  0.7416194
       0.9375000                  0.7734581
       0.9062500                  0.5221870
       0.8750000                  0.5135768
       0.8437500                  0.4477191
       0.8125000                  0.2899886
       0.7812500                  0.3797306
       0.7500000                  0.1747756
       0.7187500                  0.2577768
       0.6875000                  0.1662239
       0.6562500                  0.1115823
       0.6250000                  0.1862557
       0.5937500                  0.0201024
       0.5625000                  0.1528193
       0.5312500                  0.0259364
       0.5000000                  0.0557801
       0.4687500                  0.0877589
       0.4375000                 -0.0368005
       0.4062500                  0.1162089
       0.3750000                 -0.0484625
       0.3437500                  0.0591863
       0.3125000                  0.0258589
       0.2812500                 -0.0449824
       0.2500000                  0.1066384
       0.2187500                 -0.0989455
       0.1875000                  0.0982093
       0.1562500                 -0.0358615
       0.1250000                 -0.0230878

AVERAGE TEMPERATURE =     2.007
```